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The ethics of negative emissions

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Non-technical abstract

Limiting dangerous climate change is widely believed to require negative emissions. This prospect has sparked concerns about whether negative emissions could be scaled up quickly enough, along with concerns about their likely ethical costs. Building upon scenario modelling, this paper examines ethical concerns with negative emissions via the comparison of three alternate climate futures. This paper shows that the severity of concerns depends upon implementation conditions, and especially the extent of deferred mitigation. Negative emissions can be a valuable means of limiting dangerous climate change, or an unjust gamble against the future.

Technical abstract

Limiting dangerous climate change is widely believed to require negative emissions. This prospect has sparked concerns about whether negative emissions could be scaled up quickly enough, along with concerns about their potential ethical costs. To date, however, ethical analysis of negative emissions has been very limited. In this paper, three main concerns are identified, namely that negative emissions may obstruct mitigation both in climate modelling and in policy; that they may encourage a dangerous policy gamble; and that they may overestimate our ability to manage the carbon cycle and thus to deliver significant carbon removal. This paper then attempts an assessment of their potential severity via the comparison of three alternate climate futures. This paper shows that the severity of concerns depends greatly upon implementation conditions, and especially the extent of deferred mitigation. Consequently, negative emissions can be either a valuable means of limiting dangerous climate change, or an unjust gamble against the future.

1. The overlooked ethics of negative emissions

With the signing of the Paris Agreement, the international community pledged to limit global temperature rise to 'well below' 2°C. This seems unlikely to be achieved by conventional mitigation alone. Around 87% of the Intergovernmental Panel on Climate Change (IPCC)'s 2°C scenarios include 'negative emissions techniques' (NETs) [1], while the more stringent 1.5°C target pushes this number to 100% [2]. By expanding the remaining carbon budget, NETs render current emissions 'overshooting' in the first half of the century compatible with stringent warming targets by the century's end [3]. As national emissions targets continue to fall well short of the Paris goals [4], NETs become increasingly indispensable.

However, NETs also raise serious ethical concerns. In a widely cited commentary, Anderson and Peters claim that NETs are "an unjust and high-stakes gamble" [5] that might not work, and which would be ethically unacceptable if it did. Others also point to a 'bet' on NETs emerging, involving a gamble on successful implementation at extremely large scales to compensate for stalled mitigation [1]. Despite this, NETs remain marginal components of a normative literature still dominated by discussion of solar radiation management (SRM).[i]

General references to 'geoengineering' can obscure the ethical differences between NETs and SRM. These stem from their different characteristics and aims. First, while SRM merely masks the radiative forcing of atmospheric emissions, NETs remove atmospheric carbon. Classifications sometimes locate NETs alongside conventional mitigation since both share the aim of reducing atmospheric emissions concentrations.[ii] Second, the most-discussed SRM technique, sulfate aerosol injection (SAI), is potentially fast acting and may be very

[i]For instance, several leading volumes of essays on the ethics of geoengineering are almost entirely devoted to SRM (see [6–8]).
[ii]Heyward argues that NETs ought to remain distinct from mitigation in order to distinguish between initial inputs of emissions (i.e. conventional mitigation), and negative emissions which seek to balance the emissions budget comprising both inputs and outputs [9].

inexpensive,[iii] while NETs are medium-timescale options with costs comparable to mitigation. Third, unlike SRM, most NETs could be implemented within particular jurisdictions. There are also substantial differences between particular techniques. Much of the controversy about NETs to date is directed at bioenergy with carbon capture and storage (BECCS), a technique which removes carbon as biomass is grown and sequesters this underground when biomass is burnt. Substantially less tends to be said about other techniques, including afforestation and reforestation (AR); forms of enhanced weathering (EW) involving the dispersal of crushed silicates upon soils or of carbonate and silicate materials in the ocean; direct air capture (DAC), which extracts CO_2 from the atmosphere via chemical solvents, or via calcium or sodium-based 'wet scrubbing'; ocean fertilization (OF) using iron particles to increase CO_2 absorption; and soil carbon sequestration (SCS), which increases the carbon stored in organic matter contained in soils, and restores previously degraded soils [3].[iv] Given these differences, it is reasonable to examine the ethical implications of individual techniques on their merits [13,14].

To date, however, this has not occurred. Instead, the ethics of NETs remains largely overlooked.[v] This may be due to a fourth difference. Grasping the potential implications of NETs requires reflecting upon scenarios created by integrated assessment models (IAMs). Unsurprisingly, ethicists tend not to be well-informed about IAMs, nor about their underlying assumptions. Unlike SRM, which has provoked significant debate despite the availability of relatively little modelling, the uncertainties and risks raised by NETs depend greatly upon assumptions about how NETs might be implemented. These assumptions are reflected in and illustrated by IAMs. Thus, while the Royal Society concluded that NETs pose 'fewer uncertainties and risks' than SRM [22], IAMs reveal that this judgement may be true given some assumptions about the future, or false given others. Assessing the ethics of NETs requires reflecting upon these various possibilities, and the potential trade-offs these imply for climate mitigation, sustainable development and global justice.[vi] In order to do so, ethical reflection must be grounded in scenario evidence. At the same time, analysis must also go beyond this evidence. Not only are scenarios at best merely indicative of the future, they implicitly build upon assumptions that are by no means ethically neutral. These normative assumptions are seldom made explicit or adequately interrogated. There is thus a danger that some normative claims (e.g. historical responsibility) will be 'framed out' via scenario design itself [24]. There is also a danger of reproducing expert visions of technological futures, while reducing questions of value to epistemic questions of quantified distribution or technological feasibility [25].[vii]

The aim of this paper is thus twofold: to clarify the ethical issues raised by NETs, and to attempt an assessment of their severity via the comparison of different climate futures. The comparative, interdisciplinary approach adopted here promises to be of greater relevance for climate policy than existing ethical analyses, which engage only fleetingly (if at all) with integrated assessment modelling [26]. In the next section, I sketch three concerns that appear particularly urgent. First, there is the potential for NETs to displace near-term mitigation. Second, there is a potentially risky and dangerous 'bet' on NETs emerging. Third, it may be dangerously hubristic to assume that large-scale implementation of NETs can be adequately controlled or managed.

2. Three key concerns: mitigation obstruction, betting and hubris

2.1. NETs as mitigation obstruction (or 'moral hazard')

Anderson and Peters declare NETs to be a 'moral hazard par excellence' [5]. This general concern is widespread in the ethics of geoengineering. Indeed, prior to Crutzen's intervention [27], concerns with an SRM moral hazard prevented widespread discussion [28].[viii] Originally from insurance, moral hazards arise when there is perverse incentivization of risky behaviour. But as Hale notes [31], a moral hazard need not be a moral problem unless the behaviour incentivized is itself morally bad. The basic concern seems better expressed as mitigation obstruction [32,33].[ix] In fact, there are two senses in which NETs might obstruct mitigation. The first is embedded within climate modelling, which we might label the mitigation obstruction by design. NETs inevitably displace some near-term mitigation. Since scenarios aim to minimize mitigation costs over the century, the inclusion of NETs (an assumption labelled 'full technological availability' among modellers) alters the distribution of mitigation costs over the century.[x] Introducing NETs into IAMs increases near-term emissions compared with a non-NETs scenario. This increase means that near-term climate action is less stringent and hence less costly. This is not because NETs make near-term mitigation more expensive, but because the availability of NETs lowers the aggregated cost of mitigation over the course of the century. This effect is widely recognized among modellers [36–40]. The extent of mitigation obstructed by scenario design is potentially very large. In one comparison, near-term mitigation is greater by 9.1 gigatonnes of CO_2 by 2030 when NETs were excluded [41].[xi] Nonetheless, mitigation obstruction is not necessarily morally problematic [33]. Indeed, as we will see below, adequate ethical assessment of this requires reflection upon mitigation modelling. But as we will also see, some forms of mitigation obstruction raise a number of serious ethical concerns, especially in large overshoot scenarios reliant upon late extreme implementation of NETs. The inclusion of NETs within scenarios raises ethical questions about appropriate research design, such as whether we should assume the complete availability of technologies that are currently unproven at scale or assumed knowledge of all indirect side effects.

[iii] Although early estimates (e.g. [10]) are unreliable since they do not include any indirect costs of SRM. These costs now appear to be substantial [11].

[iv] AR and SCS present few obvious risks and could provide improvements to agricultural output, improvements to water and air quality, and cultural goods. Both are also inexpensive and SCS in particular may be cost-negative [12].

[v] Although this appears to be changing (see [15]). For discussion of BECCS, see [16]; for OF, see [17]; for brief discussion of DAC and EW, see (respectively) [18,19]. For a more general discussion of SRM and NETs permissibility, see [20,21].

[vi] This is to take what Caney calls an 'integrationist' approach to climate justice [23].

[vii] While the concerns raised in this paper concern SRM, they appear generalizable to NETs.

[viii] In light of concerns with moral hazard, Schneider reported internal resistance to the inclusion of geoengineering within the US National Research Council's 1992 report [29]. The moral hazard label was first applied to geoengineering by Keith [30].

[ix] Another way to capture this is Keith's concept of 'risk compensation' [34], that is, when risk-taking by agents adapts in response to changes in the perception of a risk. For analysis of risk compensation regarding SRM and NETs, see [35].

[x] This includes technologies like CCS and also nuclear power.

[xi] This is an absolute figure. In this comparison, CCS is constrained, which limits both CCS-dependent BECCS and DAC.

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Second, there is the extent to which NETs may be used to displace mitigation at the political level. Call this the political mitigation obstruction. There is dispute about whether NETs have already encouraged this [5,42].[xii] Indeed, exposure to geoengineering appears to suggest a reverse effect in public attitudes [44,45] or perhaps no effect at all [35]. However, experiments based upon polling members of the public tell us little about whether policy makers view the availability of NETs (or SRM for that matter) as a justification for pursuing less mitigation now.[xiii] As Gardiner argues [46], current climate policy inertia coupled with incentives to 'pass the buck' continue to justify moral hazard/mitigation obstruction concerns. And as Shue argues [16], NETs may become a convenient excuse for little near-term mitigation.[xiv] In assessing such concerns, it is worth remembering that mitigation scenarios with and without NETs assume that policymakers are actually committed to limiting warming to 2°C. However, the continued support for investments in fossil energy, especially coal power, by multilateral development banks may indicate little appetite for decarbonization over the short to medium term. In this political climate, NETs may provide a convenient excuse for less mitigation now.

2.2. Betting on NETs

Given political incentives to defer mitigation, a policy bet may emerge in which NETs are increasingly relied upon while mitigation stalls. This is a bet upon the ability to massively upscale technologies that are largely unproven at scale. For instance, much recent modelling features BECCS at very large, sometimes staggering, scales. Implementing BECCS to remove around 3.3 gigatonnes of carbon per year is estimated to "require a land area of approximately 380–700 Mha in 2100" [48]. Anderson and Peters protest that this is equivalent to "one to two times the area of India" [5]. But in the second half of the century, NETs (again typically BECCS) are often envisaged to remove between 10–20 gigatonnes of carbon. Understandably, there is considerable scepticism that such upscaling is possible [49,50]. While there are already many renewables in operation, there is currently only one functioning BECCS facility, only a few DAC prototypes, and no EW.[xv] Scaling up BECCS to anywhere near this extent would require constructing hundreds of thousands of facilities. There appears to be some evasion about the feasibility of this. For instance, in a recent commentary van Vuuren *et al.* claim that the upscaling of NETs in recent models is 'not unrealistic' [51], but this assertion is supported with nothing more than a survey of IAM experts themselves, which is in fact ambivalent about this point [52].[xvi] While the authors concede that large-scale deployment of NETs may not be feasible within the next two decades, the models they refer to already feature NETs at large scales during this period.[xvii] Upscaling of other techniques is by no means guaranteed either. For instance, large-scale EW would require the creation of a global mining industry rivalling all present-day mining activity. For DAC, obstacles include prohibitive costs, sourcing plentiful clean energy and sufficient geological storage. We might mark the concern about upscaling by referring to NETs as techniques rather than technologies, reserving the latter term for functioning socio-technical systems [53]. This would signal the enormity of scaling up such techniques to the extent required for significant net carbon removal. Although upscaling NETs remains an urgent challenge, this continues to be underappreciated in both science and policy [54]. Upscaling NETs is not a secure proposition and depends greatly on complementary policies such as carbon pricing, without which carbon capture and storage (CCS)-reliant techniques such as BECCS and DAC would never become competitive in time [55].

This takes us to the second aspect, namely whether the ethical costs of such a bet will be acceptable. A key ethical question is how to fairly distribute the benefits and burdens of any large-scale implementation of NETs. BECCS at scale could threaten food security and biodiversity, along with access to energy and water [56]. Even without NETs, however, the bioenergy component of mitigation scenarios is very substantial and may increase if NETs are excluded [57]. OF is currently subject to a moratorium given concerns regarding its ecological effects [58]. DAC, like the similarly CCS-reliant BECCS, raises concerns regarding the security of carbon stored in geological reservoirs, including leakage, risks of seismic activity and the contamination of aquifers [59]. For EW, the dispersal of millions of tons of crushed minerals onto land and ocean ecosystems may have adverse ecological effects and some compounds are toxic at high concentrations. As Lawford-Smith and Currie point out [19], side effects of EW may be displaced onto those downstream, especially in the tropics where EW may be most effective, but where there is already great underprivilege. But such a bet also concerns the distribution of risk, since a bet on NETs might be unjust even if it worked. According to Shue [16], betting on NETs would displace risks from those undertaking the gamble onto others, namely the global poor, who could not possibly consent to this, while predominantly benefitting existing polluters and wealthy members of the current generation who would pay slightly less for mitigation. However, this argument might be resisted, since the more stringent 1.5°C target requires greater use of NETs and cannot be achieved by conventional mitigation alone. NETs might thus result in less severe climate impacts, which would seem to be more just. Moreover, a policy of 'wise overshooting' is at least conceivable, in which short-term emissions help developing countries eliminate extreme poverty [20].

2.3. NETs and hubris

Concerns with hubris have long been a part of the ethics of geoengineering [60]. Unjustified arrogance in our ability to control complex natural systems may be reflected in plans to greatly intervene in and manage 'nature'. A related concern is technological optimism, that is, misplaced confidence in the efficacy of technological solutions to socially created problems. Indeed, both are components of a worldview of mastery over nature [61]. If humanity has already unintentionally stumbled into the Anthropocene by becoming the dominant planetary agent [62], we may worry about the sort of agent that emerges in an 'intentional' Anthropocene in which human action deliberately seeks to shape planetary processes. While this might appear far-fetched,

[xii] Hamilton argues that CCS has already displaced mitigation over the past decade [43].

[xiii] There is also a significant knowledge disparity between policy makers and members of the public, where the latter face substantial barriers in becoming informed about climate policy or geoengineering research.

[xiv] Self-serving rationalizations of this sort may be a symptom of what Gardiner labels moral corruption, that is, the tendency to evade our moral obligations [46,47].

[xv] Nonetheless, soil carbon and AR are both cheap, scalable and readily available. The main constraint upon AR is the availability of land.

[xvi] Vaughan and Gough argue that expert assessment concludes that the bioenergy upscaling of BECCS is likely unrealistic and infeasible, while CCS upscaling is regarded as realistic [52].

[xvii] Thanks to William Lamb for this point.

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there are historical precedents in attempts to manipulate weather [63]. For NETs, both hubris and technological optimism may be evident in overly neat assumptions of the reversibility of warming, reflecting a paradigm of carbon accounting that is not supported by our currently poor understanding of carbon cycle feedbacks. Indeed, carbon removal following overshooting may have less effect upon warming than emitting less now and it may take thousands of years before some natural systems (e.g. ice sheets) return to their earlier equilibrium [64]. While NETs do not represent a pure case of control or manipulation, implementing NETs at very large scales implies major disruptions in land-use and biogeochemical flows [48]. Given that human beings already appropriate approximately one quarter of global net primary production by vegetation [65], the very large implementation of land-dependent techniques such as BECCS within many models may be seriously hubristic. Implementing other techniques at such scales may similarly overestimate both feasibility and the safety, while underestimating adverse effects. For instance, achieving the more stringent 1.5°C target requires between 400–1000 gigatonnes of CO_2 to be removed from the atmosphere via NETs [1,2]. At current rates, utilizing BECCS or DAC to achieve this would imply storing 10–25 years of global CO_2 emissions under the Earth's crust. There are great dangers in overestimating our ability to do this justly, safely or effectively. A further aspect of hubris relates to the perceived 'naturalness' of technologies. There may be less concern about NETs that appear to enhance natural systems, such as SCS and AR, although for the latter this may depend upon the kind of reforestation envisaged (for instance, monocrop plantations compared to reforestation of existing ecosystems).[xviii]

Let us summarize the discussion to this point. We have seen that NETs obstruct mitigation within modelled scenarios and may incentivize delayed mitigation at the political level. NETs may feature in a policy gamble involving less mitigation now, despite being unproven at scale and despite the social and environmental risks this implies. And modelling of NETs at very large scales may seriously overestimate the ability to implement them justly or effectively. While these appear to be serious concerns, it is difficult to determine their severity in the absence of assumptions about future conditions. As we will see, there is no single way in which NETs might be implemented in future. Even in pursuit of the same mitigation targets, and implemented at similar scales, particular techniques do not pose the same risks or challenges. Indeed, it is misleading to speak of 'large-scale' NETs in anything but the most general sense.[xix] Expanding upon this insight via consideration of alternative climate futures would move beyond vague or prima facie permissibility assessments, while making transparent the risks and benefits. I turn to this challenge in the next section.

3. Assessing NETs under three alternate climate futures

In order to choose between different futures, we must be able to imagine them first. Although we might identify possible harms or risks of different negative emissions techniques, this depends upon highly stylized assumptions about future implementation. Obviously, we do not know the circumstances under which NETs might be used. These circumstances include the climate targets pursued (i.e. 2 or 1.5°C), global emissions trajectories, development trends including population growth and poverty alleviation, technological innovation, international cooperation and so on. The wide variety of possible implementation scenarios imply markedly different risks or benefits from NETs.

One way to illustrate the ethical implications of such complex options is to reflect upon future scenarios. The latest development of pathway analysis features five climate futures, the 'Shared Socioeconomic Pathways' (SSPs) [66]. The SSPs are hypothetical worlds estimating alternative rates of economic development, technological change, population dynamics, greenhouse gas emissions, the state of geopolitics and so on. They will likely play a crucial role in future IPCC assessments [67]. The SSPs feature divergent policy narratives and are used to model and quantify developments over the century [68]. Each relies upon a baseline emissions trajectory in the absence of climate policies and envisages different degrees of reliance upon NETs.[xx] Given space constraints, I limit myself to comparison of three SSPs. However, two caveats are in order. First, much existing modelling (including the SSPs) features only two techniques, BECCS and AR. Nonetheless, I also consider the implications of other techniques on the basis of what has been identified above. Second, these reflections cannot be more than indicative since we do not know what sort of societies will exist in future and what priorities these societies will have. As we will see, assumptions of this sort determine the severity of concerns with NETs.[xxi]

Let us begin with an alarming example. Consider SSP5, which is a climate future envisioning a continuation of fossil-fuelled development for most of the century [69]. SSP5 implies the greatest overshooting of atmospheric greenhouse gas concentrations, and the greatest requirement for carbon removal. Although considered a worst-case climate scenario with a baseline warming of greater than 5°C, SSP5 is still 'technically feasible' with the 2°C target. The achievement of this goal would require implementing NETs at seemingly incredible scales. Assumptions such as these reflect an extremely dangerous bet on negative emissions. In the first place, the lack of effective climate policies for most of the century implies that upscaling would be very costly, and for this reason unlikely. Moreover, the size of the NETs gamble in an SSP5 world is staggering. Because of this, any side effects from NETs are also likely to be extreme. For instance, under SSP5 bioenergy becomes the dominant global driver of cropland expansion after 2050. At these scales, land-based NETs would create very severe conflicts between agriculture, bioenergy and AR, especially in key areas such as the tropics, greatly increasing extinction pressures and biodiversity loss. Such a scenario appears closest to what Shue has in mind when labelling BECCS as a seriously unjust climate gamble. Given biophysical limits to land-based techniques, DAC in conjunction with conventional CCS may be more likely. But this would raise the same problem of DAC functioning as a back-stop technology, the upscaling of which remained speculative (and extremely costly) in the absence

[xviii] Characterizing DAC as akin to 'artificial trees' seems to increase its public appeal, while SAI also benefits from being framed as a 'natural' technique via analogy with a volcanic eruption [44].

[xix] Thanks to Henry Shue for pointing this out.

[xx] The SSP narratives are highly generalized pathways consistent with many emissions concentration scenarios. Recall that over 900 scenarios were modelled within the AR5. The discussion that follows draws upon quantitative estimates in [68] unless otherwise indicated.

[xxi] In the discussion which follows, I do not mean to imply that NETs are causally responsible for each of the effects considered. This would be to misunderstand the SSPs, which are integrated models based upon broader social and economic logics. Instead, NETs are best viewed as contributing factors in the development of SSP pathways, rather than as isolated causes.

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of complementary climate policies. Perhaps the worst aspect of such a bet is that it seems to create a forced choice for future generations between NET implementation at extreme scales and abandoning the 2°C target.

SSP5 also raises extreme concerns with hubris. The sheer scale of carbon removal required may dramatically overestimate our abilities to understand and control natural systems. One key uncertainty are thresholds for biophysical 'tipping points' [70]. The most well-known examples include the melting of Arctic permafrost, which would release enormous quantities of both carbon dioxide and methane, the melting of Greenland and Antarctic ice sheets, which would significantly raise sea levels, or the disruption of Atlantic meridional overturning circulation. However, modelled pathways currently ignore tipping points. Shue argues that this is a further reason to think that NETs at scale would be gravely unjust [16]. All the same, if the thresholds for tipping points are higher, NETs may instead buy time until they are eclipsed.

SSP5 represents an extreme case of mitigation obstruction. With no effective climate policies until late in the century, fossil fuel reliance would expand beyond business as usual assumptions. According to the SSP5 narrative, this development leads to substantial human development gains, lifting many out of extreme poverty. While this appears implausible given current global trends of worsening inequality [71], under such a scenario policymakers would likely continue to see climate mitigation and development as mutually exclusive goals.[xxii] Perhaps more realistically, the continued presence of fossil fuel industries for much of the century implies severe obstacles to mitigation and a prioritization of currently powerful economic interests. The steepness of reductions required in the second half of the century, the lack of salience of climate change as a policy concern, and the path-dependencies of fossil fuel infrastructure point to an extreme mitigation obstruction generally. In such a case, NETs would be expected to further exacerbate this mitigation obstruction. Now, if significantly delaying mitigation is unjust despite the future availability of NETs [16,21], SSP5 would present the clearest case of climate injustice. Although SSP5 may be technically feasible with the 2°C target according to narrow modelling assumptions, the upscaling this implies is extremely implausible, ignores climate damages including the possibility of exceeding tipping points and implies unbounded optimism about the potential of NETs. Of course, this judgement may be tempered if the hopeful assumption of extreme poverty reduction in SSP5 were borne out. But even if it were, there would instead be an intergenerational conflict between those made better off from fossil fuelled development and future generations who stand to be worse off because of climate change. Nonetheless, such a dynamic could not be continued indefinitely since a point would eventually be reached at which climate damages undermined potential poverty reductions.

Contrast this with SSP4, a climate future in which inequality increases steadily over the century, both between nations and within societies [72]. SSP4 is a tale of two worlds, one which is high-technology, wealthy, well-educated and at stable population levels, and one which is low-technology, labour-intensive, uneducated, much poorer but much more populous. While less extreme than in the previous world, the risks of a bet on NETs may nonetheless be severe. Mitigation occurs very slowly until the mid-century mark, locking in a substantial requirement for NETs. How large this requirement turns out to be, and the distribution of risks that emerge as a result, depends greatly upon the priorities of the increasingly powerful elites controlling policy in SSP4. These elites are likely to be less accountable even to their own citizens as inequality increases. But the interests of those elsewhere, and especially the poorest among them, are likely to fare significantly worse. Consider that SSP4 features much regional and global variation in the effects of the land-based impact of NETs. Cropland devoted to bioenergy would greatly expand, especially in low- or middle-income countries. While forest coverage would increase in middle- and high-income countries, such gains entail greater deforestation in poor countries to meet the agricultural demands of the wealthy world. This will greatly increase global food prices, disproportionately affecting the poor. The carbon price is predicted to be above \$2000/tCO_2 by 2100, a very large increase that would inflate food prices seven times over [72]. In a very unequal world, this is likely to cause mass starvation [16]. Avoiding food shortages or sudden food price increases would require the establishment of agreements on sustainable biomass production, without which a kind of 'energy colonialism' may emerge incentivizing conversion of forests, existing cropland and marginal land in the global South [73]. But in a world like SSP4, this seems unlikely. Elites may be incentivized to gamble on larger NETs implementation if risks would be primarily borne by the increasingly powerless global poor.

SSP4 implies considerable, although mixed concerns with hubris. First, SSP4 implies a shift to a more technocratic global paradigm of planetary management. For instance, unlike in other worlds, nuclear power becomes available in SSP4, which would both decrease reliance on fossil energy and provide the power input requirements of DAC. As elites became less accountable, the choice of siting locations of carbon storage and nuclear waste are likely to be imposed from above rather than subject to public consultation or deliberation. A greater willingness by elites to engage in large-scale management of ecological systems implies few restrictions on future research, likely opening the door to more extensive experimentation with EW and OF, and perhaps also SRM. However, while implying an outlook of dominance or mastery over nature, technocratic responses do not necessarily entail worse sustainability outcomes. For instance, in order to preserve authoritarian political regimes, elites may choose to prioritize longer-term environmental sustainability.

Obstruction of near-term mitigation is implied by the SSP4 narrative itself, which states that the global elite will react 'quickly and decisively' to implement climate policy, but only in the second half of the century. Although this is not due to NETs alone, the availability of NETs would exacerbate such an effect. But as with hubris, assessing the role of NETs in such a situation requires knowing the priorities of elites. For instance, elites may decide to delay mitigation longer since NETs are assumed to be available and since there is little accountability for any potential side effects, especially if these could be displaced elsewhere.

Finally, let us consider an optimistic case. As we noted, NETs make possible the achievement of more stringent warming targets. Considered solely in terms of primary climate impacts, lower climate stabilization outcomes appear closer to the requirements of justice. While this conclusion can be undermined by the potential side effects of NETs, such side effects may be more benign. Consider SSP1, an optimistic future in which a variety of global development goals are achieved while economic growth is

[xxii]The development gains in SSP5 imply diverting course earlier, as more informed and politically capable societies would seem to increasingly recognize the need for ambitious mitigation.

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de-coupled from emissions [74]. As a result, ethical concerns with NETs appear relatively minimal in such a world. Consider the potential bet upon NETs. In SSP1, in contrast to all other modelled worlds, effective mitigation policies are implemented in the first half of the century. The result is the smallest concentration of atmospheric emissions and the smallest overshooting. This renders both the 1.5 and 2°C targets much easier to achieve and implies the smallest requirements for negative emissions. Although NETs are still required for 1.5°C, and remain likely even for 2°C, there is much less overshooting and hence much less deferral of mitigation to the second half of the century. Under such optimistic assumptions, implementing even solely land-based NETs to achieve 2°C would enable a gain of 63 million hectares in forest land [75]. This implies that the sorts of alarming biophysical implications associated with BECCS do not apply to such a future. Moreover, the implementation of effective climate policies, especially carbon pricing, early in the century would lessen concerns with NETs upscaling. Instead, innovation driven by carbon pricing would lead to cheaper, more effective technologies being available earlier in the century. The optimism of SSP1 extends to geopolitics, where greater cooperation between nations decreases mitigation and NETs challenges even further. Given this, there is also the least likelihood that risks will be deferred onto the vulnerable, who have a more effective voice in political decisions than in other worlds.

Unsurprisingly for a 'green growth' scenario, the potential hubris of NETs also appears dramatically lower. SSP1 features the smallest global human footprint given the lowest population of all worlds, decreased materialism and status consumption, and decreased demand for animal products. Economic activity gradually shifts so as to prioritize wellbeing improvements and global consciousness about environmental problems improves greatly. These trends are diametrically opposed to SSP5, which envisions an expansion of current unsustainable consumption patterns of the rich world to most of the global population. Given the growth in environmental consciousness in SSP1, NETs with larger effects on natural systems such as BECCS may be perceived to be more problematic and hence may be less utilized. Techniques that enhance natural processes, such as AR and SCS, may be preferred, while techniques involving the dispersal of chemical or mineral compounds into open ecological systems, such as OF and ocean-based EW, may be discarded on principle in this more ecologically-minded future.

Finally, the potential for mitigation obstruction would be least worrisome in such a future world. SSP1 features the smallest absolute level of emissions and the fewest economic, political and social barriers to effective mitigation. Given such assumptions, it is also least likely that ambitious mitigation would be substantially deferred. At the political level, there would be relatively little incentive for policy-makers to defer mitigation in order to pursue other short-term goals. This is because a variety of sustainable development goals are envisioned to be achieved in SSP1, including universal education, the eradication of extreme poverty and sustainable economic growth decoupled from emissions. While this presents a comparatively rosy picture, it is worth noting reasons for scepticism. SSP1 envisions a future in which sustainable growth is de-coupled from emissions, while moderate population growth and improved living standards do not worsen existing burdens upon planetary resources. Leaving aside the economic debate about whether de-coupling of economic growth and emissions is possible, it is in any case clear that such a future is currently very far from reality.

4. Conclusion

The crucial question to ask seems to be: where are we now? Are we on track for the extreme challenges of an SSP5 world, the rosy future or an SSP1 world, or something in between? Although modelling is no more than indicative of future developments, we can be surer about where we are starting from. Unfortunately, this is not promising. As Fuss *et al.* note, given our current global emissions trajectory and the absence of effective decarbonization policy, we are "not in a position to discard the negative emissions option easily", notwithstanding the risks involved [1]. Any future implementation of NETs should be contingent upon, and not a substitute for, ambitious mitigation now.

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