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The Physics and Ecology of Mining Carbon Dioxide from the Atmosphere by Ecosystems

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Abstract

Reforestation and managing ecosystems have been proposed as ways to mitigate global warming and offset anthropogenic carbon emissions. The ability of individual plants and ecosystems to mine carbon dioxide from the atmosphere, as defined by rates and cumulative amounts, are limited by laws of physics and ecological principles. The intent of our opinion piece is to provide perspective and conditionality on how well individual plants and ecosystems sequester carbon. We discuss how these processes vary in scale, time and space. We also discuss unintended consequences that may arise when working with complex systems. We base our analysis on 1163 site-years of direct eddy covariance measurements of gross and net carbon fluxes from 155 sites spread across the globe.

We arrive at six take-home points. First, increasing the capacity of ecosystem photosynthesis is the most obvious way to mine CO₂ from the atmosphere. Yet, the potential amount of carbon an ecosystem can assimilate by photosynthesis on an annual basis is set and scales with absorbed sunlight and available water. Second, gains of carbon by ecosystem photosynthesis are associated with large respiratory losses; efforts to improve photosynthesis will come with the cost of more respiration. Third, the rates and amount of net carbon uptake are relatively slow and low, compared to the rates and amounts and rates of carbon dioxide we release by fossil fuels combustion. Fourth, huge amounts of land area for ecosystems will be needed to be an effective long-term carbon sink to mitigate anthropogenic carbon emissions. Fifth, the effectiveness of using this land as a long-term carbon sink will be contingent on its ability to sustain a permanent carbon sink, on the availability of adequate water, on competing needs for other ecological services and providing food and fiber for the human population. Sixth, converting land to forests or wetlands may have unintended costs such as biophysical feedbacks which warm the local climate, the occupation of plants which produce volatile organic carbon compounds that are precursors to air pollution and the production of prodigious amounts of methane by anaerobic wetlands.

We do not argue that planting forests or restoring deep-rooted perennial grassland and wetlands should not be part of the climate mitigation portfolio. Rather, given the urgency of reducing carbon in the atmosphere, we want the reader to consider that efforts and resources may be better aimed towards reducing and eliminating carbon emissions from fossil fuel combustion, like solar voltaic farms, than only supplementing business-as-usual policies with projects on carbon sequestration by ecosystems.

Keywords

Carbon sequestration, climate mitigation, unintended consequences, ecosystem ecology, biophysical ecology, biosphere-atmosphere interactions

Introduction

Many of us want to stop and reverse the steady rise in CO₂ in the atmosphere by planting a tree in our back yard or by contributing to larger efforts that will plant millions of trees. How well collections of plants are able to mine CO₂ from the atmosphere depends upon numerous biophysical and ecological factors and costs that affect the conversion of photosynthesis into stored carbon compounds (Zelitch, 1975, Zhu *et al.*, 2010). First, there are energetic and water costs to producing and sustaining the plant ultrastructure that maintain these photosynthesizing leaves in an ecosystem. Second, ecosystem photosynthesis scales with the amount of absorbed sunlight and water available on an area basis, rather than on a plant basis. Third, plant maintenance and growth respiration releases some of this fixed carbon back to the atmosphere. Fourth, heterotrophic respiration of exuded photosynthate and dead plant material by microbes (Kuzyakov, 2010) and disturbance by fire, insects and pathogens, landslides or floods (Amiro *et al.*, 2010) return carbon to the atmosphere on ecosystem time and space scales. Consequently, the ability of an ecosystem to sequester carbon will decline with age (Odum, 1969).

The aim of this opinion piece is to discuss the physical and ecological limits to mining carbon dioxide from the atmosphere by ecosystem. In writing this opinion, we draw upon a database that produces information on gross and net carbon fluxes at annual time scales and ecosystem space scales (Baldocchi, 2008, Pastorello *et al.*, 2016). The FLUXNET 2015, tier-one, database consists of 1163 site-years of gross and net carbon dioxide fluxes that were measured directly with the eddy covariance method (Baldocchi, 2003) from 155 sites spread across the world (details of the measurements and data are described in the supplemental material).

The content of this opinion will revolve around the ability of individual plants and ecosystems to sequester carbon and mitigate global warming. We will first discuss the bottom up perspective, which adds up all the carbon sequestered by plants as they are born, grow and die. Then, we will discuss top-down perspective. It is based on the constraint that there is only so much solar energy, water and nutrients per unit area. In this case, the number of plants and size of plants must adjust to their space.

Bottom-Up Scaling

The metabolic rate of a forest is the sum of the number of trees of a class size per unit area (N_i) times the metabolic rate of that class size (B_i) (Enquist, 2002). From Kleiber's Law (Kleiber, 1947), we know that the metabolic rate of an individual scales with its mass (M) to the $3/4$ power.

$$B \propto M^{3/4} \quad (1)$$

How many trees can be supported on a plot of land and how big can they grow? We know from self-thinning studies that the mass of trees of a certain size class is a function of the number of trees per unit area to the $-4/3$ power (Enquist *et al.*, 1998).

$$M \propto N^{-4/3} \quad (2)$$

We can solve for the metabolic rate of the ecosystem, by inverting the self-thinning law, Equation 2 ($N \propto M^{-3/4}$), and multiplying it by Equation 1. In doing so, we find that the metabolic rate of the ecosystem, B_T , is scale invariant with the mass, M^0 :

$$B_T = \sum_{i=1}^n N_i B_i \propto \sum_{i=1}^n M_i^{3/4} \sim \sum_{i=1}^n M_i^0 \quad (3)$$

The object lesson of this scaling exercise is that physics sets the upper limits on ecosystem metabolism. The carbon sequestering organisms of an ecosystem will be occupied with either a large number of small trees or a small number of large trees (Enquist, 2002). This occurs because there is only so much solar radiation available on a given area of land. Consequently, many seedlings will die or remain stunted because they do not get enough sunlight, water or nutrients to sustain themselves as they grow and crowd one another.

Top-Down Scaling

In principle, collections of plants are biological solar collectors that turn sunlight into chemical energy. At this juncture, let's address the following question: 'what is the potential amount of carbon that can be fixed, given the incident solar energy on a unit area of land and how is it used for carbon assimilation?'

The gross amount of carbon sequestered per unit area on a yearly basis is called gross primary production. Using a widely-used identity, gross primary production ($\text{g C m}^{-2} \text{y}^{-1}$) is a product of the flux density of visible light (photosynthetically active radiation, Q_p), times the fraction of visible light that is absorbed ($fpar$) times the light use efficiency (LUE) (Monteith, 1977, Ruimy *et al.*, 1995).

$$GPP = Q_p \cdot fpar \cdot LUE \quad (4)$$

The terms in Equation 4 are the knobs we can turn to evaluate how effectively an ecosystem may be able to extract carbon dioxide from the atmosphere through carbon assimilation. We will show in the following that the amount of carbon dioxide assimilated by different types of vegetation will depend upon their climate and latitude, leaf area index, photosynthetic capacity and length of growth season. We will also highlight that there is only so much sunlight available on a unit area of land and this available energy will set the upper limit on gross and net carbon uptake.

First, how much light is available? Global solar radiation is the shortwave radiation on a horizontal surface. The integrated amount of global solar radiation that is available over the course of a year is a function of latitude (Figure 1).

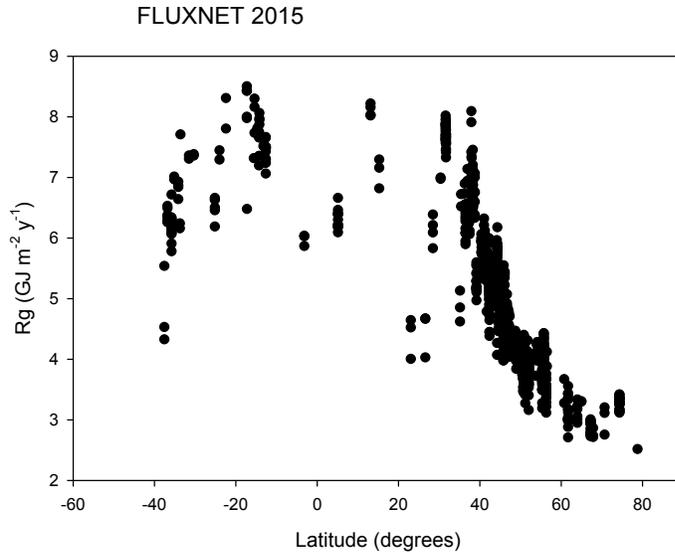


Figure 1 Latitudinal distribution of global solar radiation, R_g , integrated over a year. These data come from the Tier 1 FLUXNET 2015 dataset.

Maximum incident sunlight (up to $8 \text{ GJ m}^{-2} \text{ y}^{-1}$) occurs near the tropical belts (± 23.5 degrees), the zone of major deserts. Elsewhere, there is less solar radiation. Locations around the Equator receive between 5 and $7 \text{ GJ m}^{-2} \text{ y}^{-1}$ because of the presence of clouds. Less sunlight is available at higher latitudes because the sun is lower in the sky.

Photosynthesis is driven only by radiation in the photosynthetically-active, portion of the electromagnetic spectrum, which consists of light energy with wavelengths between 0.4 and $0.7 \mu\text{m}$. A useful conversion between moles of quanta of photosynthetically active radiation (Q_p , $\mu\text{mol m}^{-2} \text{ s}^{-1}$) and energy flux density of global radiation (R_g , $\text{J m}^{-2} \text{ s}^{-1}$) is (Ross, 1980):

$$Q_p = 4.6 \cdot R_g / 2 \quad (5)$$

The fraction of absorbed sunlight, $fpar$, scales with leaf area index (Myneni *et al.*, 1997, Sellers, 1985). In principle, $fpar$ saturates at a value between 0.9 and 1.0 as leaf area index reaches $5 \text{ m}^2 \text{ m}^{-2}$; $fpar$ is as low as 0.3 for an open canopy with a leaf area index near one. It is also notable that leaf area index scales with water balance (Baldocchi & Meyers, 1998, Grier & Running, 1977). Ecosystems with ample rainfall will form closed canopies with high leaf area indices ($3\text{-}6 \text{ m}^2 \text{ m}^{-2}$). Those with deficient rainfall will form open canopies with low leaf area indices ($< 3 \text{ m}^2 \text{ m}^{-2}$).

Light use efficiency quantifies how well ecosystems convert sunlight into stored chemical energy. Under ideal growing conditions peak light use efficiency of ecosystems, on a mole CO_2 per mole quanta of photosynthetically active radiation, is on the order of 2% (Loomis & Williams, 1963, Ruimy *et al.*, 1995, Zhu *et al.*, 2010). Over the course of a year, many annual crops and deciduous plants do not achieve this level of efficiency. They experience much seasonal variability in their light use efficiency due to factors like phenology and seasonal drought (Garbulsky *et al.*, 2014, Stocker *et al.*, 2018, Turner *et al.*, 2003).

We can quantify how well ecosystems achieve maximal rates of photosynthesis by comparing measured values of GPP with potential values (GPP_{max}) computed as a function of available sunlight, maximal $fpar$ and the assumption that light use efficiency is 0.02. Figure 2 shows the comparison between annual

sums of actual and potential photosynthesis of 155 ecosystems distributed across the globe. The best performing ecosystems tend to be tropical forests, which operate near potential rates, as defined by the one to one line; they assimilate between 2000 and 4000 g C m⁻² y⁻¹ because they have ample soil moisture and year-round growing seasons. Most other ecosystems assimilate between 100 and 2000 g C m⁻² y⁻¹, which is a fraction of theoretical GPP_{max} values. Why is actual photosynthesis such a low fraction of potential photosynthesis? First, many ecosystems are physiologically active for less than one-half of the year (Ganguly *et al.*, 2010). Second, limitations in available water and nutrients prevent closed canopies from forming and capturing most of the incoming sunlight (Baldocchi & Meyers, 1998).

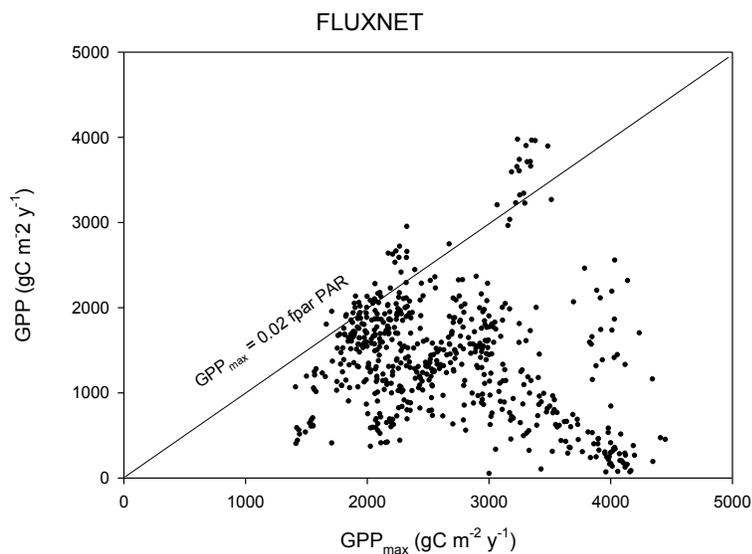


Figure 2 Comparison of measured values of gross primary production and computations of maximal rates, based on light availability and the assumption of 2% photosynthetic efficiency. Data represent sites spanning the climatic and ecological spaces of the world. These data come from the Tier 1 FLUXNET 2015 dataset.

The next knobs we examine are those that convert gross, assimilatory carbon fluxes to net fluxes. Net ecosystem exchange is comprised of the balance between GPP and the sum of autotrophic respiration and heterotrophic respiration (Chapin *et al.*, 2006). Given that we have bounded the amount of gross primary production that is possible, how much of this assimilated carbon is lost by respiration processes? Annual measurements of gross and net carbon fluxes reveal that on average 82% of assimilated carbon is lost as ecosystem respiration and that 84% of the variance in ecosystem respiration is explained by variations in GPP (Figure 3). We add that subsampling these data reveal that the ratio can be as low as 0.66 in nutrient rich forests, as high as 0.93 in nutrient poor forests (Fernández-Martínez *et al.*, 2014) and it is above 1 for disturbed sites (Baldocchi, 2008). The tight coupling between GPP and R_{eco} also reveals that factors that lead to an increase in annual photosynthesis are associated with an increase in ecosystem respiration, and vice versa.

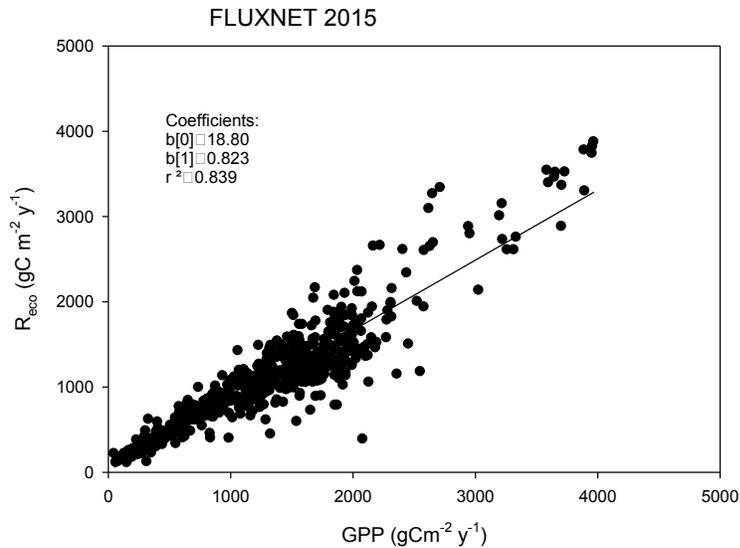


Figure 3 The relationship between annual sums of measured gross primary production (GPP) and ecosystem respiration (R_{eco}). These data come from the Tier 1 FLUXNET 2015 dataset. A linear regression is fit through the data

The main points to be drawn are that annual photosynthesis varies across the world's climate and ecological spaces, many plants are inactive for a large portion of the year, and that the magnitude of the net carbon sink, when viewed across the globe on annual time scales and under field conditions, is relatively small due to the large respiratory costs that are needed to support its carbon assimilating infrastructure. Consequently, there is not a 'one size fits all' solution with regards to using collections of plants and ecosystems to mine CO₂ from the atmosphere. These results are also consistent with agricultural literature that is replete with studies that show little to no relationship between photosynthetic potential and yield (Gifford & Evans, 1981, Long *et al.*, 2006), yielding evidence of a carbon paradox.

So far we have discussed, net ecosystem exchange. Examining ecosystem carbon budgets on longer time scales and larger space scales one encounters additional carbon losses due to fire, disease, insects, flooding, landslides, windthrow; this defines net biome exchange (Chapin *et al.*, 2006, Schulze, 2006).

If we are to add to the Earth's ability to sequester carbon, it may be most desirable to plant trees where they are not growing, as in the semi-arid steppes of the world. Unfortunately, there are hydrologic factors that act to limit the amount of carbon ecosystems can sequester, too. First and foremost, there is tight coupling between ecosystem carbon assimilation and water use (Law *et al.*, 2002, Tanner & Sinclair, 1983). How much water is needed? This question is answered with data in Figure 4, a plot between measurements of annual gross primary production and annual evaporation. First, ecosystems need to evaporate at least 200 mm y⁻¹ to sustain any photosynthesis, so rainfall must exceed this amount. Second, trees use more water than grasses, crops and shrubs (Jiang & Ryu, 2016, Williams *et al.*, 2012); evergreen broadleaved forests use over 900 mm y⁻¹ of water; deciduous broadleaved forests use nearly 700 mm y⁻¹; evergreen needleleaf forests use over 500 mm y⁻¹; crops use over 600 mm y⁻¹; and savannas under 500 mm y⁻¹.

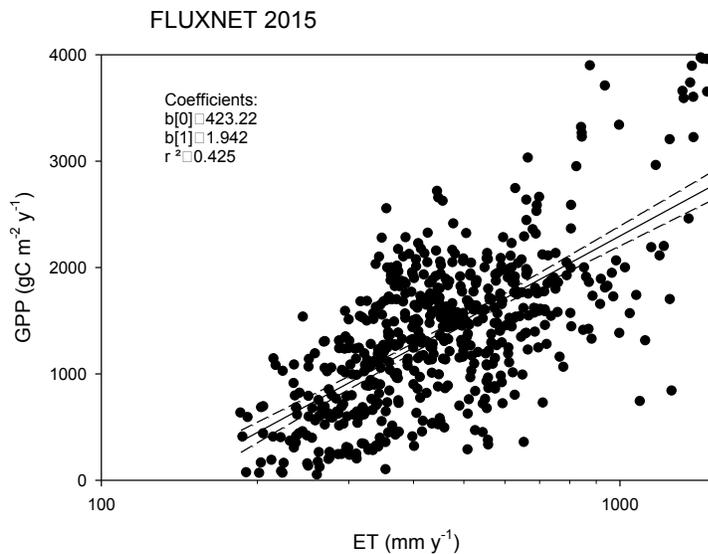


Figure 4 The relation between annual evaporation and annual gross primary production, as sensed at sites spanning the climatic and ecological spaces of the world. These data come from the Tier 1 FLUXNET 2015 dataset.

Land use change associated with using plants to mine carbon from the atmosphere, can sometimes lead to unintended consequences. In semi-arid regions, converting sparsely vegetated land to forests may reduce runoff to streams and deplete ground water (Jackson *et al.*, 2005). If there is not enough soil moisture, a forest with relatively low leaf area will form (Scheffer *et al.*, 2005), which limits its ability to absorb light and assimilate carbon. Trees can also release volatile organic compounds that contribute to the production of tropospheric ozone among many other effects on atmospheric chemistry and even climate (Peñuelas & Llusia, 2003). And we must consider the permanence, the residence time, of sequestered carbon by plants. Many ecosystems in the drier portions of the world experience periodic fires, on decadal to century time scales (Randerson *et al.*, 2005).

The degree to which vegetation exerts a biophysical forcing on cooling the climate depends on surface and planetary albedo, surface temperature and the aerodynamic and surface conductance (Burakowski *et al.*). In the humid tropics, subtropics and temperate zones, forests absorb more solar radiation and evaporate more than grasslands under clear skies. The water vapor that they transpire into the atmosphere causes evaporative cooling and forms clouds, which reflect sunlight. These two sets of processes can act to cool the atmosphere where forests are planted compared to grasslands (Burakowski *et al.*, Jackson *et al.*, 2008, Juang *et al.*, 2007). In contrast, a forest planted in the desert of Israel, takes up more carbon than surrounding shrub vegetation, but it also absorbs more solar and longwave radiation than surrounding vegetation (Rotenberg & Yakir, 2010). The high aerodynamic roughness of that forest allows it to convect sensible heat back to the atmosphere. This efficient convection enables the surface temperature of the forest to be up to 5 C cooler than surrounding

vegetation. The energy has to go somewhere, and in such conditions this extra sensible heat warms the air column over the forest (Baldocchi & Ma, 2013, Burakowski *et al.*).

In sum, vegetating a bare landscape with forests produces offsetting and non-intuitive effects, causing an energy paradox. One set of biogeochemical processes may lead to the temperature of the vegetation to cool, relative to surrounding vegetation, but under certain conditions biophysical processes can cause the exchange of energy to warm the air column (Jackson *et al.*, 2008). We should not forget, though, that forests provide many co-equal ecological services such as maintaining biodiversity and habitat, building and conserving soil and storing water.

Because ecosystems are modest carbon sinks it will take an enormous land area to offset the amount of carbon emitted by fossil fuel combustion and cement production. At present, humans emit about 10 Pg C y^{-1} and oceans and ecosystems are taking up about one-half of these emissions (Le Quéré *et al.*, 2016). If we are to offset the remainder by reforestation, afforestation and/or ecosystem restoration, we would need an additional 42 million square kilometers of newly vegetated landscapes. This order of magnitude estimate assumes an average net carbon uptake rate (238 g C $m^{-2} y^{-1}$; Figure 3) and this area estimate does not consider additional losses of carbon when ecosystems burn, are harvested or die from drought, insects and pathogens. Nor does this area estimate consider the amount of land that is not available or is unsuitable because it is already dedicated to providing food and fiber for a burgeoning world population, is too cold or too dry to support significant rates of carbon uptake.

Concluding Remarks

We arrive at six take-home points. First, plants act like solar collectors by using sunlight to assimilate carbon dioxide and turn it into chemical energy. Increasing the capacity of ecosystem photosynthesis is the most obvious way to mine CO₂ from the atmosphere. Consequently, much energy and resources are being directed to take more carbon out of the atmosphere by improving the ability of plant photosynthesis (Blankenship *et al.*, 2011, Kromdijk *et al.*, 2016). While such efforts are laudable, we must be cautious on relying on increasing photosynthesis as the solution to mine more carbon dioxide out of the atmosphere. The intent of this essay is to better inform us that there are upper limits in the ability of ecosystems to sequester carbon and these limits are set by physical and ecological laws and scales with available sunlight and water. If ecosystems are to become stronger carbon sinks, the logical knobs to turn are increase: 1) the length of the growing season; 2) leaf area index to absorb more sunlight and 3) photosynthetic capacity.

Second, we cannot expect to increase ecosystem photosynthesis without a concomitant increase in ecosystem respiration and a formidable amount of water use. Restoring wetlands is appealing because their flooded nature inhibits heterotrophic respiration by restricting the diffusion of oxygen. Wetlands are strong candidates to be carbon sinks because they are known to be reservoirs of vast amounts of sequestered carbon in the form of peat. But the area of available land for wetlands is limited and, when flooded, wetlands produce prodigious amounts of methane, a very strong greenhouse gas (Knox *et al.*, 2014).

Third, the rates and amount of net carbon uptake are slow and low compared to the rates and amounts of carbon dioxide we release by fossil fuels combustion. In other words, ecosystem solutions work on ecosystem time scales and will not solve our problem immediately.

Fourth, huge amounts of land area for ecosystems will be needed to be an effective long-term carbon sink to mitigate anthropogenic carbon emissions. To mine more carbon dioxide from the atmosphere it will be necessary to find locales with ample water, which may not be readily available.

Fifth, the effectiveness of using this land as a long-term carbon sink will be contingent on its ability to sustain a permanent carbon sink, on the availability of adequate water, on competing needs for other ecological services and providing food and fiber for the human population.

Sixth, converting land to forests or wetlands may have unintended costs such as biophysical feedbacks which warm the local climate, the occupation of plants which produce volatile organic carbon compounds that are precursors to air pollution and the production of prodigious amounts of methane by anaerobic wetlands.

Finally, we must be prepared to ask and answer if it is more feasible to decarbonize our energy system and reduce carbon emissions, rather than rely on ecosystems take up carbon in a slow, incremental way over current baseline? Current and expected carbon emissions exceeding 10 Pg C/y will not be offset by using such simple solutions as growing more trees (Le Quéré *et al.*, 2016). If push comes to shove, it may be more effective to implement more efficient and continuous means of solar energy conversion. Solar panels have a greater potential to convert sunlight into energy than ecosystems; they have efficiencies reaching 20% and operate year-round. Nor, do they use as much water.

We do not argue that planting forests, wetlands and deep-rooted perennial grasslands should not be part of the climate mitigation portfolio (Pacala & Socolow, 2004). Given the urgency of reducing carbon dioxide in the atmosphere, the relatively low potential of converting solar energy to stored carbon, the vast amount of land needed to be significant carbon sinks and the risk for unintended consequences, we want the reader to consider that efforts and resources may be better aimed towards reducing and eliminating carbon emissions that are associated with fossil fuel combustion.

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