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OPINION

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The physics and ecology of mining carbon dioxide from the atmosphere by ecosystems

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Abstract

Reforesting and managing ecosystems have been proposed as ways to mitigate global warming and offset anthropogenic carbon emissions. The intent of our opinion piece is to provide a perspective on how well plants and ecosystems sequester carbon. The ability of individual plants and ecosystems to mine carbon dioxide from the atmosphere, as defined by rates and cumulative amounts, is limited by laws of physics and ecological principles. Consequently, 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. Managing ecosystems to sequester carbon can also cause unintended consequences to arise. In this paper, we articulate a series of key take-home points. First, the potential amount of carbon an ecosystem can assimilate on an annual basis scales with absorbed sunlight, which varies with latitude, leaf area index and available water. Second, 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 carbon sink to mitigate anthropogenic carbon emissions. Fifth, the effectiveness of using this land as a carbon sink will depend on its ability to remain as a permanent carbon sink. Sixth, converting land to forests or wetlands may have unintended costs that warm the local climate, such as changing albedo, increasing surface roughness or releasing other greenhouse gases. We based our analysis on 1,163 site-years of direct eddy covariance measurements of gross and net carbon fluxes from 155 sites across the globe.

KEYWORDS

biophysical ecology, carbon sequestration, climate mitigation, ecosystem ecology, unintended consequences

1 | INTRODUCTION

Many of us want to stop and reverse the steady rise in CO_2 in the atmosphere. Natural solutions include planting a tree in our back yard or buying carbon credits that finance the planting of millions of trees and restoring ecosystems (Griscom et al., 2017).

How well collections of plants mine CO_2 from the atmosphere depends upon numerous biophysical and ecological factors. First, there are energetic costs in producing and sustaining the plant structure that maintains photosynthesizing leaves in an ecosystem and in converting photosynthate into stored carbon compounds (Penning De Vries, 1975; Zelitch, 1975; Zhu, Long, & Ort, 2010). Second, ecosystem photosynthesis scales with the amount of absorbed sunlight and water available on an area basis, which varies across the globe. Third, plant maintenance and growth respiration releases some of this fixed carbon back to the atmosphere. Fourth, there are theoretical limits to how many plants or trees one can pack on a finite area of land and how big they will be (Enquist, 2002). This is because there is a set amount of solar radiation, water and nutrients available on a given area of land. Consequently, the carbon assimilation by an ecosystem of a finite area will be conducted by a combination of a large number of small trees or a small number of large trees (Enquist, 2002). Fifth, heterotrophic respiration of exuded photosynthate and dead plant material by microbes (Kuzyakov, 2010) and disturbance by fire, mortality, insects and pathogens, landslides or floods (Amiro et al., 2010) return an additional increment of carbon to the atmosphere on ecosystem time and space scales. And sixth, the ability of an ecosystem to sequester carbon will vary with its age (Besnard et al., 2018; Coursolle et al., 2012; Odum, 1969).

The aim of this opinion piece is to discuss the physical and ecological limits to mining carbon dioxide from the atmosphere by ecosystems. 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., 2017). The FLUXNET 2015, tier-one, database consists of 1,163 site-years of gross and net carbon dioxide fluxes that were measured directly with the eddy covariance method (Baldocchi, 2003) at 155 sites spread across the world (details of the measurements and data are described in the Supporting information).

2 | HOW MUCH CARBON CAN ECOSYSTEMS SEQUESTER ON A YEARLY BASIS?

To estimate how much carbon can be assimilated by an ecosystem, let's consider plants as biological solar collectors that turn sunlight into chemical energy. Annual gross primary production (g C m^{-2} year^{-1}) can be estimated as 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, Jarvis, Baldocchi, & Saugier, 1995).

$$\mathrm{GPP} = Q_p \cdot \mathrm{fpar} \cdot \mathrm{LUE} \quad (1)$$

The terms in Equation 1 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.

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

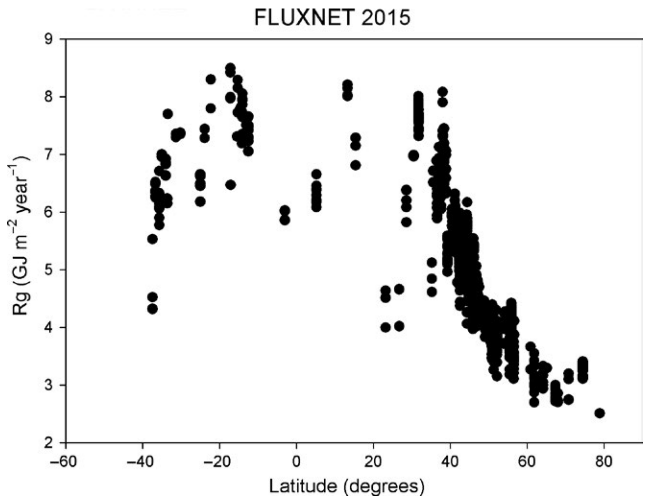

FIGURE 1 Latitudinal distribution of global solar radiation, R_g, integrated over a year. These data come from the Tier 1 FLUXNET 2015 dataset

Maximum values of global solar radiation (up to 8 GJ m^{-2} year^{-1}) occur outside 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 GJ m^{-2} year^{-1} because of the presence of clouds. Less sunlight (<3 GJ m^{-2} year^{-1}) 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 μm. A useful conversion between moles of quanta of photosynthetically active radiation (Q_p, μmol m^{-2} s^{-1}) and energy flux density of global radiation (R_g, J m^{-2} s^{-1}) is (Ross, 1980):

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

The fraction of absorbed sunlight, fpar, scales with leaf area index (Myneni, Nemani, & Running, 1997; Sellers, 1985). Ecosystems with ample rainfall form closed canopies with high leaf area indices (3–6 m^2/m^2). Ecosystems with deficient rainfall form open canopies with low leaf area indices (<3 m^2/m^2) (Baldocchi & Meyers, 1998; Grier & Running, 1977). In principle, fpar saturates at a value between 0.9 and 1.0 as leaf area index reaches 5 m^2 m^{-2}. For open canopies with a leaf area index near one, fpar is as low as 0.3.

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 associated with phenology, temperature stress and seasonal drought (Garbulsky, Filella, Verger, & Penuelas, 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 maximal values (GPP_{max}); GPP_{max} is 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 measured sums of annual GPP and calculations of GPP_{max} from 155 ecosystems distributed across the globe. The best performing ecosystems are tropical, evergreen, broadleaved forests, which operate near maximal rates, as defined by the one to one line; they assimilate between 2,000 and 4,000 g C m^{-2} $year^{-1}$ because they have ample soil moisture and year-round growing seasons. Most other ecosystems assimilate between 100 and 2000 g C m^{-2} $year^{-1}$, which is a fraction of their 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 due to temperature (Ganguly, Friedl, Tan, Zhang, & Verma, 2010). Second, limitations in available water and nutrients prevent closed canopies from forming and capturing most of the incoming sunlight.

The next knobs we examine are those that convert gross, assimilatory carbon fluxes to net carbon fluxes. Net ecosystem carbon 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 slope can be as low as 0.66 in nutrient-rich forests, it approaches one for nutrient-poor forests (Fernández-Martínez et al., 2014), and ecosystem respiration exceeds ecosystem photosynthesis of disturbed sites (Baldocchi, 2008) and the grasslands in this figure. 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.

The main point to be drawn, here, is that the magnitude of the net carbon sink, when viewed across the globe on annual time scales and under field conditions, is relatively small (Baldocchi, 2014); it is −156 ± 284 gC m^{-2} $year^{-1}$. This is due in part to the large respiratory costs that are needed to support carbon assimilating infrastructure (Gifford, 1994; Waring, Landsberg, & Williams, 1998). Examining ecosystem carbon budgets on longer time scales and larger space scales, one encounters additional carbon loses due to fire, disease, insects and other disturbances; this defines net biome exchange (Chapin et al., 2006; Pan, Birdsey, Phillips, & Jackson, 2013; Schulze, 2006). We also observe that assimilation by many ecosystems is inactive for a large portion of the year, while ecosystem respiration occurs year-round.

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 used to fix carbon? This question is answered with data in Figure 4, a plot between measurements of annual gross primary production and annual evaporation. On average, GPP increases by about 2.97 ± 1.33 gC m^{-2} $year^{-1}$ with each millimeter increase in evaporation. Consequently, ecosystems that assimilate over 3,000 gC m^{-2} $year^{-1}$ must evaporate over 1,000 mm of water per year. For ecosystem photosynthesis to exceed zero, rainfall must exceed 135 mm/year to offset soil evaporation from bare soil.

3 | UNINTENDED CONSEQUENCES OF MINING CO_2 FROM THE ATMOSPHERE

Land use change is needed to cause an additionality in carbon uptake. Unfortunately, land use change can sometimes lead to unintended

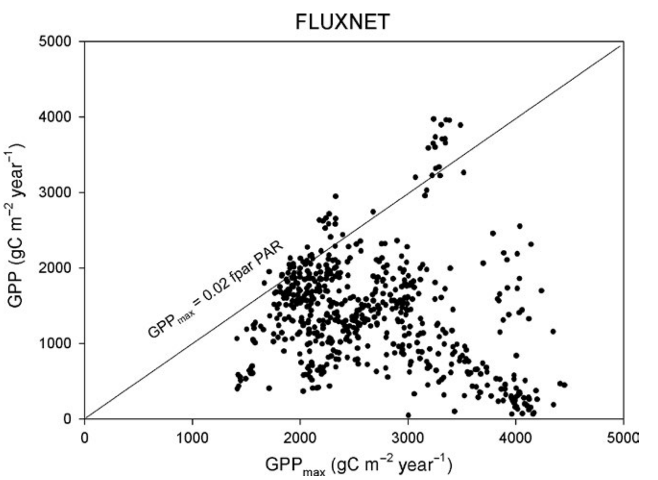

FIGURE 2 Comparison of measured values of gross primary production and computations of maximal rates based on light availability and the assumption of 2% photosynthetic efficiency. Data represent sites spanning the climatic and ecological spaces of the world. These data come from the Tier 1 FLUXNET 2015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

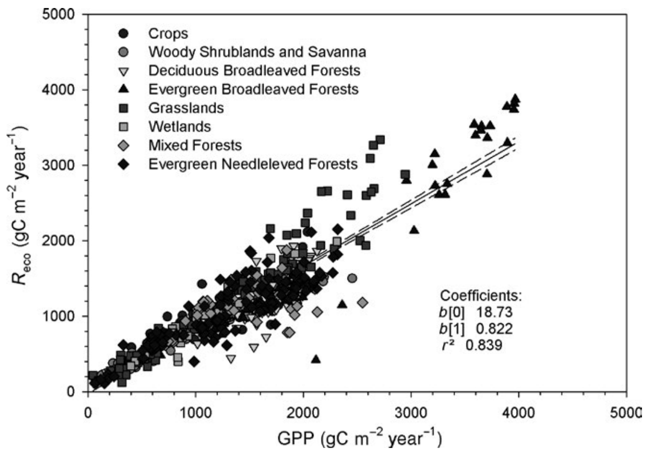

FIGURE 3 The relationship between annual sums of measured gross primary production (GPP) and ecosystem respiration (R_{eco}). These data come from the Tier 1 FLUXNET 2015 dataset. A linear regression is fit through the data. Colors denote major functional groups

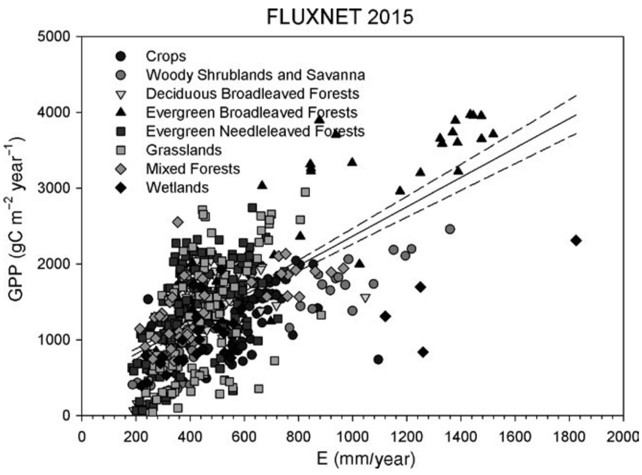

FIGURE 4 The relation between annual evaporation and annual gross primary production, as sensed at sites spanning the climatic and ecological spaces of the world. These data come from the Tier 1 FLUXNET 2015 dataset. The log transformed linear regression is GPP = −5,631 + 2,642 log(E)

consequences. 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 semiarid steppes of the world. However, converting sparsely vegetation 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 or shrubland with relatively low leaf area will form (Scheffer, Holmgren, Brovkin, & Claussen, 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 and mortality by drought on decadal to century time scales (Allen et al., 2010; 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., 2018). 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., 2018; Jackson et al., 2008; Juang, Katul, Siqueira, Stoy, & Novick, 2007). Forests planted in the semiarid and arid regions may take up more carbon than native shrub vegetation, but these introduced ecosystems also absorbs more solar and longwave radiation than surrounding vegetation (Rotenberg & Yakir, 2010). Furthermore, the higher aerodynamic roughness of forests allows them to convect sensible heat back to the atmosphere, which warms the air column over the forest (Baldocchi & Ma, 2013; Burakowski et al., 2018).

In sum, vegetating a bare landscape with forests, to enhance carbon sequestration, produces offsetting and nonintuitive 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.

At present, humans emit about 10 Pg C/year and oceans and ecosystems are taking up about one-half of these emissions (Le Quéré et al., 2018). Because ecosystems are modest carbon sinks, it will take an enormous amount of additional land area to offset the amount of carbon emitted by fossil fuel combustion and cement production. If we are to offset the yearly addition of carbon (5 PgC/year) into the atmosphere by reforestation, afforestation and/or ecosystem restoration, given natural rates of net carbon uptake, we will need to an extraordinary large area of land. A recent analysis of 20 natural climate solutions estimates that 48 M km^2 are needed with a portfolio of reforestation, avoided forest conversion, forest and crop management, and peat restoration (Griscom et al., 2017). This is more than the combined areas of the United States, Canada and Russia. Even more land area will be needed if less-effective paths are used.

4 | CONCLUSIONS

The intent of this essay is to inform us on the limits in the ability of natural ecosystems to sequester carbon and offset anthropogenic emissions. These limits are set by physical and ecological laws, and they scale with absorbed sunlight and available water. Consequently, we conclude that there is not a “one size fits all” solution with regards to prescribing where and how to best mine CO_2 from the atmosphere with plants and ecosystems.

Based on our analysis, we arrive at eight 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 CO_2 from the atmosphere. At this writing, much energy and resources are being directed to take more carbon out of the atmosphere by improving the ability of plant photosynthesis through genomics and proteomics (Blankenship et al., 2011; Kromdijk et al., 2016). While such efforts are laudable, we must be cautious about relying on increasing photosynthesis as the solution to mine more carbon dioxide out of the atmosphere. The agricultural literature is replete with studies that show little to no relationship between photosynthetic potential and yield (Gifford & Evans, 1981; Long, Zhu, Naidu, & Ort, 2006), yielding evidence of a carbon paradox. To increase ecosystem photosynthesis, the logical knobs to turn are to increase: (a) length of the growing season by substituting perennial for annuals; (b) leaf area index by increasing the water balance and (c) photosynthetic capacity by retaining nitrogen. Doing any of these activities on large enough space scales will remain a challenge.

Second, we cannot expect to increase ecosystem photosynthesis without a concomitant increase in ecosystem respiration and a formidable amount of water use.

Third, restoring wetlands is appealing because their flooded nature inhibits heterotrophic respiration by restricting the diffusion of oxygen. The productivity of northern wetlands and peatlands is limited by temperature and length of growing season, and the productivity of coastal wetlands is limited by salinity (Watson & Byrne, 2009). Freshwater temperate wetlands are highly productive, but they produce prodigious amounts of methane, a very strong greenhouse gas (Knox et al., 2015; Petrescu et al., 2015).

Fourth, 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. Consequently, ecosystem solutions to the increasing carbon dioxide burden in the atmosphere work on ecosystem time scales, which are long, and so they will not solve our carbon problem immediately.

Fifth, 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 suitable locales with adequate water and sunlight. Much land is not available or is unsuitable because it is already dedicated to providing food and fiber for a burgeoning world population, it is privately owned, or it is too cold or too dry to support significant and additional rates of carbon uptake.

Sixth, the effectiveness of using this land as a long-term carbon sink will be contingent on its ability to sustain a permanent carbon sink. In the long term, the ability of forests to sequester carbon declines with age. And, in many parts of the world, fire is a re-occurring process.

Seventh, converting land to forests may have unintended costs such as biophysical feedbacks which warm the local climate and the occupation of plants which produce volatile organic carbon compounds that are precursors to air pollution.

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/year will not be offset by using such simple solutions as growing more trees. Overall, 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 and deep-rooted perennial grasslands or restoring peatlands and wetlands should not be part of the climate mitigation portfolio (Griscom et al., 2017; 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 political capital and resources may be better aimed toward more effective and immediate solutions, like reducing and eliminating carbon emissions that are associated with fossil fuel combustion.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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