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Terrestrial carbon losses from mountaintop coal mining offset regional forest carbon sequestration in the 21st century

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Abstract

Studies that quantify the spatial and temporal variability of carbon sources and sinks provide process-level information for the prediction of future levels of atmospheric carbon dioxide as well as verification of current emission agreements. Assessments of carbon sources and sinks for North America that compare top-down atmospheric constraints with bottom-up inventories find particularly large carbon sinks in the southeastern US. However, this southeastern US sink may be impacted by extreme land-use disturbance events due to mountaintop coal mining (MCM). Here we apply ecosystem modeling and field experiment data to quantify the potential impact of future mountaintop coal mining on the carbon budget of the southern Appalachian forest region. For projections based on historical mining rates, grassland reclamation, and the continued regrowth of un-mined forests, we find that the southern Appalachian forests switch from a net carbon sink to a net carbon source by year 2025–33 with a 30%–35% loss in terrestrial carbon stocks relative to a scenario with no future mining by the year 2100. Alternatively, scenarios of forest sequestration due to the effect of CO₂ fertilization result in a 15%–24% loss in terrestrial carbon stocks by the year 2100 for mining scenarios relative to scenarios with no future mining. These results suggest that while power plant stack emissions are the dominant life-cycle stage in coal-fired electricity, accounting for mountaintop coal mining in bottom-up inventories may be a critical component of regional carbon budgets.

Keywords: extreme event, carbon cycle, mountaintop coal mining, forest regrowth, CO₂ fertilization, southeastern US

1. Introduction

Forest ecosystems are important sinks for anthropogenic emissions of CO₂ to the Earth's atmosphere [1, 2]. A dominant driver of this forest sink in North America is

secondary forest regrowth in the southeastern US region [3]. Another important driver is enhanced forest uptake due to the enhanced forest growth stimulated by rising atmospheric CO₂ concentrations. Though the magnitude of this CO₂ fertilization effect is equivocal, experimental and model results support the concept that enhanced rates of net primary production (NPP), moderated by enhanced soil respiration, may sequester large amounts of CO₂ with upper estimates showing a 30% increase in global terrestrial C stocks



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Figure 1. Southern Appalachian forest region (shaded).

by 2100 [4]. For temperate forests, recent free-air CO₂ enrichment (FACE) experiments provide constraints of NPP increases under elevated CO₂ projected into the 21st century and show NPP enhancements ranging from 9% to 24% for atmospheric CO₂ concentrations of 550 ppm [5].

With temperate forests in mind, mountaintop coal mining (MCM) practices present an extreme event in the face of continued forest carbon sequestration [6]. MCM practices are common in the southern Appalachian forest region (SAFR) of the southeastern United States (figure 1). The SAFR is approximately 5 million ha in area and is a forest region often associated with a net terrestrial C sink. MCM methods are a forest disturbance agent where the plant carbon is clearcut and thereafter scraped from the land surface, and soil organic carbon is removed and drastically disturbed [7]. Approximately 15 000 ha yr⁻¹ are mined via MCM methods in the SAFR due to the abundance of high quality, low sulfur coal [8, 9]. Coal from the region accounts for approximately 25% of the coal produced in the United States. Based on analysis of coal reserve estimates in the SAFR and coal production rates over the past 20 years, there is ample coal supply in the region to mine at the current rate throughout the 21st century [10–14].

We hypothesized that MCM practices in the SAFR had the potential to offset projected forest carbon sequestration from regrowth and CO₂ fertilization in the 21st century. This MCM case study presents an example of perhaps unforeseen impacts associated with fossil fuel burning that can influence regional carbon budgets. This MCM study is particularly important because secondary terrestrial carbon losses associated with MCM have just recently been quantified [6, 15], and to our knowledge these estimates have not been included in projections of regional carbon budgets.

2. Methods

In order to assess the potential of MCM practices to offset projected forest carbon sequestration, we integrate

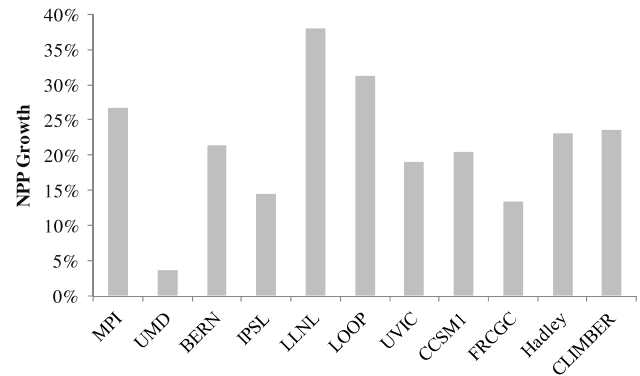


Figure 2. Growth in NPP at the time of a doubling of atmospheric CO₂ for eleven coupled carbon-climate models in the C⁴MIP experiment.

soil process modeling and field measurements as well as output from a suite of coupled climate-carbon models. We develop projections for scenarios in which no future mining occurs (section 2.1) and scenarios in which mining continues at current rates (section 2.2). The modeling approach, assumptions and uncertainties for these scenarios are discussed below.

2.1. Un-mined forest carbon stocks in the 21st century

The USDA Forest Service Carbon On Line Estimator (COLE) [16] was used to provide estimates of non-soil carbon (live tree, dead tree, under story, down dead wood, forest floor) for each county in the SAFR and the results were aggregated for the SAFR region (see table 2 in [6]). Forest soil organic carbon (SOC) stocks were based on measurements reported in [15]. In that study, 24 soil pits were excavated and sampled for SOC and bulk density in un-mined old- and second-growth forests in the region. SOC stocks were 80.6(±14.2) and 90.6(±9.6) Mg C ha⁻¹ for old- and second-growth forests, which agree well with previous estimates of forest soil stocks in the region [17].

We alternatively considered two scenarios of future carbon sequestration for either forest regrowth or CO₂ fertilization. We applied these sequestration trajectories to all of the SAFR forestlands in the un-mined scenario and to the fraction of un-mined SAFR lands in the mining scenarios. The future sequestration associated with secondary forest regrowth was accounted for using COLE estimates of carbon stocks by age class and an estimated mean current age class of 50 years [18, 19]. Future sequestration associated with rising atmospheric CO₂ concentrations was accounted for using ecosystem carbon stock projections from eleven C⁴MIP climate-carbon models [4]. These C⁴MIP models had a range of NPP enhancement rates (figure 2) that is consistent with the range of FACE experimental results in the temperate forests of the southeastern US [5]. Furthermore these C⁴MIP models included a range of soil responses to climate change that reflect the uncertainty in the strength of the soil respiration enhancement relative to the NPP enhancement as well as other climate feedbacks [20]. We applied output

from three carbon–climate models to represent a range of potential sequestration rates (UMD—low, UVIC—medium, LOOP—high).

2.2. Mining estimates and reclamation carbon in the 21st century

Future rates for the area of disturbance during MCM were estimated based on historical rates of 15 190 ha y⁻¹ [8, 9]. The 4 734 724 ha forested area of the SAFR in 2000 was based on analysis from [9]. Our projection of the current mining rate may be an overestimate if environmental regulations and competition with natural gas and other energy sources lead to a reduction in coal mining. Alternatively, our projection of the current mining rate may be an underestimate if coal mining becomes more land-use intensive as coal seams become thinner and if coal production increases in line with US DOE reference case projections [21].

The rate of carbon sequestration on reclaimed mined lands was estimated for SOC and non-soil carbon using the soil–water model, CENTURY 4.5.1 [22]. CENTURY simulations were parameterized for grass growth because existing reclamation in the SAFR has focused on erosion prevention via grasslands and bankfill stability and not reclamation with trees (US EPA 2005). CENTURY parameterization for the reclaimed grasslands is detailed in [23]. Briefly, the modeled crop was modified to reflect nitrogen fixation from leguminous species planted during reclamation, and plant production was adjusted to provide an equilibrium NPP of approximately 500 g m⁻². Lignin content of plant material was parameterized based on observations from a 12 year reclaimed site [24]. Soils were parameterized for the heavily compacted, low permeability soils on the reclaimed mining sites using field measurements of bulk density, initial SOC content and texture [15, 23]. Field data was used to calculate field capacity and wilting point of each soil layer [25]. Current reclamation practices generally distribute inorganic weathered constituents from overburden material and do not include topsoil replacement. Therefore, a spin-up simulation to estimate initial SOC stocks was not performed. Initial SOC stocks were set to near zero for model stability.

Harvesting of forest carbon prior to mining may also influence regional carbon budgets. The US Forest Service allocation of harvested forest carbon provides regionally and temporally varying estimates of carbon pools associated with harvest including wood products in use, carbon in landfill, carbon emitted with energy capture, and carbon emitted with no energy capture [26]. While carbon associated with wood products and landfills clearly result in carbon sequestration, the carbon emitted with energy capture is less certain and depends on the rate of fossil fuel displacement. If only wood products and landfill sequestration are considered as sequestered carbon, then the fraction of sequestered carbon relative to the pre-harvest non-soil carbon approaches 9% within 40 years of harvest (figure 3). If the sequestered carbon includes products, landfills, and energy capture then the fraction approach 30%. In this study we consider the sequestration effect of harvested carbon at both a 9% and

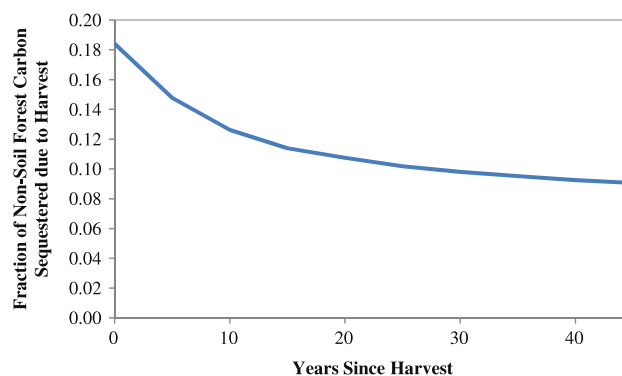


Figure 3. Harvested forest carbon that is sequestered in landfills and wood products as a fraction of the total non-soil carbon at the time of clearcut harvest for oak–pine stands in the USFS South Central region.

30% rate. These rates are consistent with assumptions used in previous work [27, 28]. These rates are specific to a 40 year period. Using the wood product data from [26] we find that a 100 year period results in 3%–16% less harvest-related sequestration than a 40 year period suggesting that our harvest accounting may be slightly conservative with respect to MCM impacts. While significant methane emissions may result from the landfills, we omit this effect because our focus is on the influence of mining on regional CO₂ budgets. Emission reductions may also result from the displacement of wood products with fossil fuel intensive construction materials. However, these emissions may be outside of the regional domain and thus not relevant to the regional CO₂ budgets we seek to inform.

3. Results

Figure 4 shows the CENTURY model results for soil and non-soil carbon sequestration on grassland reclaimed mined lands in the SAFR. After 100 years, upper and lower bounds for total terrestrial carbon (plant + soil) reclaimed to the grasslands was 52 and 61 Mg C ha⁻¹, which is one third or less of the average initial forest carbon stocks of 177 Mg C ha⁻¹.

Potential carbon sequestration trajectories from future regrowth on undisturbed lands in the SAFR are plotted in figure 5. From age classes of year 50 (average age of current forest in the SAFR) to year 100 the non-soil forest carbon can increase from 9% to 45% depending on forest type. The current carbon stocks with an age class of 100 years have a 25% increase in non-soil forest carbon relative to stocks with an age class of 50 years which is near the mean of the different forest type reforestation projections. We use this 25% regrowth trajectory for our future projections of non-mined lands.

Given the assumption that soil C stocks are unchanged by regrowth [26], the total undisturbed forest C stock in the un-mined scenario increased from 0.67 Pg C in year 2000 to 0.77 Pg C in year 2100 (figure 6, green line). In contrast, if future mining continues to occur at historical rates then 32%

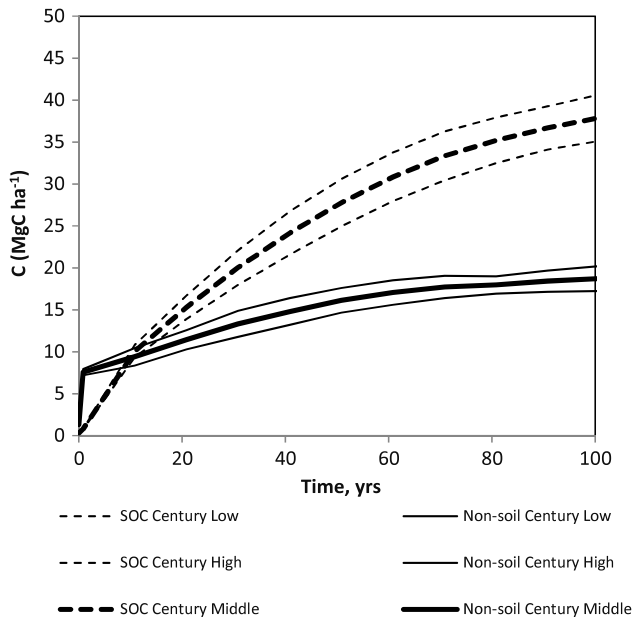


Figure 4. Soil (SOC) and non-soil carbon sequestration on reclaimed grassland sites using the CENTURY model.

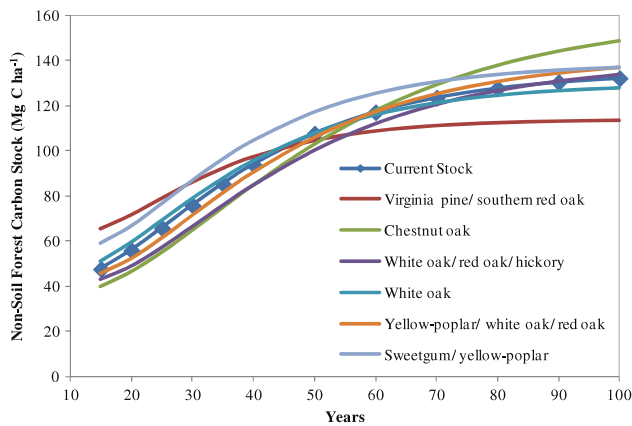


Figure 5. Non-soil carbon stocks by age class (years) in the southern Appalachian forest region from the US Forest Service Carbon Online Estimator (COLE).

of the SAFR will be deforested by 2100 resulting in forest C emissions that more than offset the regional sequestration from forest regrowth on un-mined lands (figure 6, black lines). This mining scenario accounts for carbon sequestration on the reclaimed MCM lands and the continued carbon sequestration on the undisturbed fraction of the SAFR. For this mining scenario, the SAFR switches from a net carbon sink to a net carbon source by the years 2025 and 2033 for the harvest sequestration rates of 9% and 30%, respectively. By the year 2100, the terrestrial carbon stocks in these two mining scenarios are 30%–35% lower than the un-mined scenario.

While regrowth is one potential driver of future forest sequestration, we also considered the effects of CO₂ fertilization and climate change. We use results from coupled carbon–climate models that account for a range of NPP-CO₂ sensitivities, future atmospheric CO₂ concentrations, soil respiration responses to climate change and other terrestrial

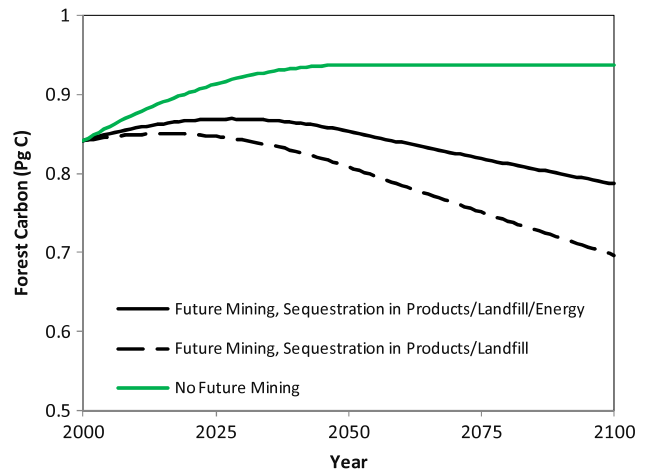


Figure 6. Forest carbon in the southern Appalachian forest region under a future scenario of continue forest regrowth with no future mining (green line) and scenarios of mountaintop coal mining at historical mining rates (black lines). Carbon is sequestered in soils and biomass in all scenarios due to sequestration on reclaimed mine lands and undisturbed forests. Harvested wood prior to mining is sequestered as wood products and landfill material (solid black line) or sequestered as wood products, landfill material and combustion with energy capture (dashed black line).

climate feedbacks. The low sequestration rate shows only a slight increase in undisturbed forest carbon stocks (figure 7(a)). This carbon–climate model has an NPP-CO₂ sensitivity of 4% which is considerably lower than the FACE experiment range for this region of 9%–24%. Despite the minimal carbon sequestration rates, the carbon loss from mining results in reductions of forest carbon of 15%–22% relative to the un-mined scenario. The scenarios with high rates of CO₂ fertilization result in a 40% increase in undisturbed carbon stocks from the year 2000 to the year 2100 (figure 7(c)). The mining scenarios result in a 17%–24% decrease in forest carbon stocks relative to the un-mined scenario by the year 2100.

4. Discussion

In both the cases of forest regrowth and CO₂ fertilization, our results suggest that continued MCM practices could more than offset regional forest carbon sequestration, changing the forests in the SAFR from a net carbon sink into a net carbon source. Only in the case of high CO₂ fertilization rates is projected forest carbon sequestration not fully offset by mining disturbances. All regrowth and CO₂ fertilization scenarios resulted in losses of SAFR forest carbon of at least 15% relative to un-mined scenarios.

The simultaneous effect of regrowth and CO₂ fertilization was not accounted for in these estimates, suggesting that our projections may be an underestimate of carbon losses associated with mining. Other sources of uncertainty that may result in an underestimate include the potential for coal demand to increase [21], for the coal extracted per hectare to decrease, and for a smaller fraction of forest carbon to be sequestered due to pre-mining wood harvest. Sources

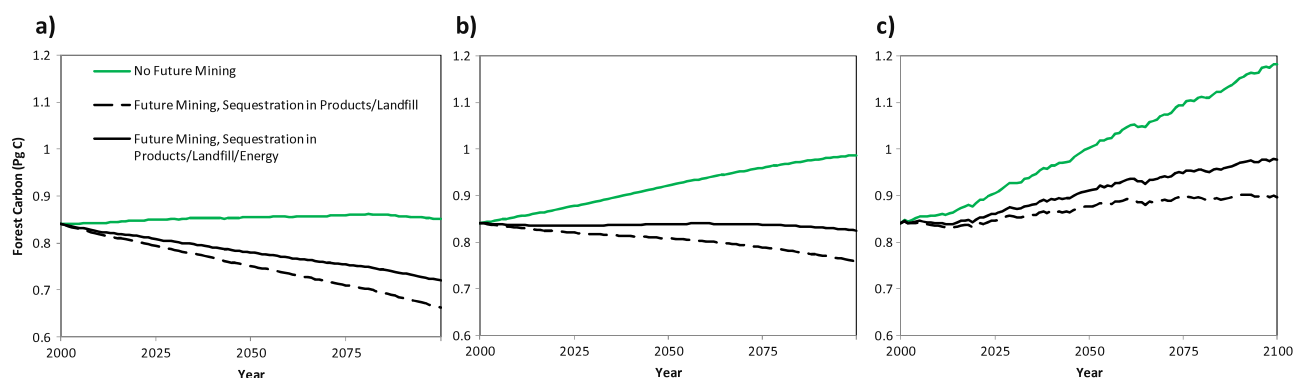


Figure 7. Projected forest carbon stocks in the southern Appalachian forest region assuming continued rate of historical mining disturbance (black lines) and no future mining (green line). Two alternative rates of CO₂ sequestration in wood products from pre-mining harvest are considered (solid black—sequestration of harvested wood through wood products, landfills and energy capture; dashed black line—sequestration of harvested wood through wood products and landfills). Three alternative rates of future carbon sequestration in forests are considered based on a range of enhancements to net ecosystem production (NEP) due to CO₂ fertilization. These rates are from three different coupled carbon–climate models for a model with low NEP growth (UMD), medium NEP growth (UVIC) and high NEP growth (LOOP).

of uncertainty that may result in an overestimate of forest carbon losses include decreased rates of coal mining due to greenhouse gas regulations and competition from other energy sources and decreased carbon sequestration in the non-mined scenario due to forest harvest that is not associated with mining. Despite these uncertainties, the range of assumptions provided in this analysis present projections that suggests the potential for significant mountaintop coal mining impacts on regional carbon budgets.

Spatially explicit constraints in our analysis make these results particularly useful for regional carbon budgets that seeks to compare top-down and bottom-up methods for exploring carbon cycle processes. This analysis is distinct from studies of carbon budgets that do not have spatial constraints. In particular, life-cycle assessment of coal-fired electricity suggests that land-use impacts from mountaintop coal mining may have a small but significant contribution to net greenhouse gas emissions relative to power plant emissions and other life-cycle stages [6].

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