Forests, Farmland, and Climate Change Mitigation in the Delaware River Basin

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Executive Summary

As a key philanthropic partner for conservation in the Delaware River Basin, the William Penn Foundation can play an important role in influencing how natural lands are managed for climate change mitigation. In this report, we review a comprehensive inventory of greenhouse gas emissions for the Delaware River Basin (DRB) and estimate the magnitude of carbon removals from forests and farmland in the basin that work to offset these emissions. We also explore how different management techniques could work to increase these carbon removals from forest and farmland. We then compare removals from forest and farmland to a range of alternative land use practices.

Communities within the DRB are a major source of greenhouse gas pollution, generating over 110 mmt CO_2e (million metric tons of carbon dioxide equivalents) in 2021, or fully 1.7% of U.S. emissions. Transportation and commercial and residential buildings are the biggest sources of emissions, with industry also playing a significant role. The DRB contains a wealth of forest and farmland resources, including 1.78 million hectares of forest and 0.62 million hectares of farmland. Forests removed an estimated 11.9 mmt CO_2e in 2021. Farmland removed 0.75 mmt CO_2e in 2021, with pastureland removing 0.90 mmt and cropland emitting 0.14 mmt CO_2e.

Significant changes in land management might have a relatively small impact on carbon removals.

Increasing the area of forests harvested for wood products could increase regional carbon sequestration because harvests will help shift the age distribution of forests from older, slow growing trees to younger, faster growing trees. However, we found that increasing the area of forestland harvested annually by 20% *reduced* basin-wide carbon removals by around 5.7%. Results were strongly dependent on assumptions about the fate of C in harvested wood products; if more wood products are directed towards long-lived uses like furniture or biochar, increasing harvest could slightly increase basin-wide removals. Changing the specific harvest technique (e.g., shifting from clearcut to seed tree and shelterwood harvest methods) could increase sequestration rates after harvest by 0.28 to 1.28 t CO_2e per hectare per year in individual stands. It is important to note that all of these harvest practices incurred a "carbon debt" in the first several decades after harvest, as the below ground and residue biomass from harvested vegetation decomposes. Because the next 20-30 years are so critical for climate action, forest harvests need to be very carefully considered as a climate mitigation strategy.

Shifting from conventional to regenerative farming practices can improve soil carbon sequestration rates at the field scale. We found that with regenerative agriculture practices including reduced tillage, crop diversity, and cover crops, farmers could increase soil carbon sequestration rates 1.17 to 1.25 t CO_2e per hectare per year. However, at the basin scale, implementing these practices on *every farm* would only result in offsetting 0.6% of annual basin-wide emissions. Limiting methane emissions from

dairy and beef cattle and nitrous oxide emissions from fertilizers and manures could also help address agriculture's contribution to regional emissions.

Comparing alternative land uses, protecting land currently in forests and farmlands emerges as a key priority. Relative to building new housing within already developed areas, building low-density residential development in recently cleared rural areas leads to increases in transportation and housing emissions. Combined with the loss of carbon from forest biomass, converting forests to low-density development could result in a net increase of 27.6 t CO_2e per hectare, per year. Focusing on just the lands in the Delaware River Watershed Initiative "Opportunity Parcels", protecting forests could prevent more than 32.1 mmt CO_2e per year of additional emissions.

Moving forward, the William Penn Foundation can have an enormous impact on climate mitigation in the DRB by continuing to support the preservation and stewardship of existing forests and farmland. The William Penn Foundation may have additional opportunities for climate action by supporting the responsible integration of solar energy production on working farmland.

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About this Report

This research was commissioned by the William Penn Foundation to support strategic planning discussions for the foundation. The project was led by Claire Jantz (Shippensburg University), with contributions from Franklin Egan (Clear Climate Strategies), Alfonso Yañez Morillo (Shippensburg University), and Nicholas Pevzner (University of Pennsylvania). Kyle Myers (Shippensburg University) provided additional assistance with research and analysis.

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Introduction, Background, and Needs

Through its Delaware River Watershed Initiative (DRWI) and other programs, the William Penn Foundation (WPF) has been working for over 20 years to foster stewardship of land and water resources in the Delaware River Basin. The Delaware River Basin (DRB) holds a wealth of forests, farmland, and other natural habitats that play a critical role in protecting water quality, conserving biodiversity, and providing a range of economically valuable goods and services. Through the DRWI, WPF works to protect natural lands and build community networks that can better manage these lands for a healthy environment.

There is an increasing awareness that globally, forests and farmland will play a critical role in drawing down greenhouse gas pollution and avoiding some of the more dire impacts of human-caused climate change. Trees and other forest plants absorb carbon dioxide (CO_2) as they grow and can store carbon in plant biomass and forest soils for decades or even centuries. Well-managed farmland can also store substantial amounts of carbon underground as soil organic matter. Climate advocates have long argued that carbon removals from forests and farmlands can help countries achieve their greenhouse gas reduction goals. For instance, the US EPA reported that land use and forestry offset 11.9% of total U.S. greenhouse gas emissions in 2021 (US EPA, 2023c). Many corporate climate action plans also rely on purchasing carbon offsets from forestry and agriculture projects to counteract their business emissions.

More locally, communities throughout the DRB are also looking to forests, farmland, and other natural lands to help address climate change challenges. Private land holders may also be engaging with the voluntary carbon offset market. Farmers can earn supplemental income by selling the carbon sequestration connected to regenerative agricultural practices through a variety of commercial platforms including Indigo Ag or Corteva. Private landholders can also earn carbon revenues on forest land by implementing management practices that increase growth and regeneration through organizations such as the American Family Forest Carbon program.

As the William Penn Foundation considers its strategic support for conservation in the DRB, important questions emerge regarding the role of forests and farmland in regional climate action and mitigation. Do carbon removals from forests and farmlands play a significant role in offsetting greenhouse gas emissions from businesses and households within the DRB? Could forest managers and farmers remove more carbon with improved management practices or better public policy? And how can William Penn Foundation align its work in the Opportunity Parcels to advance soil and water conservation goals while also optimizing the carbon removal and climate mitigation potential of forests and farmland?

In this report, we've worked to address these questions and describe quantitatively the role of forests and farmland in climate mitigation for the DRB. We conducted a comprehensive greenhouse gas inventory for the DRB, including both location-based and household consumption-based inventories. We also worked with a range of models and datasets to estimate carbon removals from forests and farmland under typical current management practices. We then extended this analysis to explore how carbon removals in forests could be increased through improved harvesting schedule techniques and how removals from farmland might be increased with regenerative agriculture practices. Finally, we compare a range of land use and land conversion scenarios to help prioritize potential actions and strategies for the Opportunity Parcels.

Greenhouse Gas Inventory for the Delaware River Basin

Two Perspectives on Regional Greenhouse Gas Emissions

This report summarizes two separate 2021 greenhouse gas inventories for communities in the DRB: a **location-based inventory** that focuses on emissions occurring within the basin's boundaries and a **consumption-based inventory** that accounts for all emissions connected to household activities and purchases.

A Note on Units

We report emissions and removals units of metric tons (t, or roughly 1.10 U.S. ton) of carbon dioxide equivalents (CO_2e) per year. Global climate change is largely caused by human emissions of carbon dioxide, methane, nitrous oxide, and other greenhouse gases. These compounds each have different effects on the atmosphere, which can be standardized relative to the 100-year "global warming potential" of carbon dioxide. For each source of emissions in these communities, we report the total of all carbon dioxide, methane, and nitrous oxide summed together as CO_2e. Figure 1 may help to relate a t CO_2e to everyday activities and quantities.

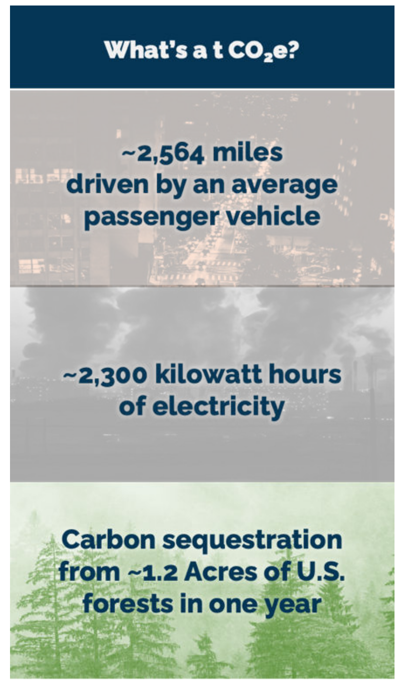


Figure 1. Examples of activities that generate or remove 1 metric ton of carbon dioxide equivalents (t CO_2e).

We developed the 2021 **location-based inventory** following the framework provided by the ICLEI USA Community Protocol (ICLEI-USA, 2019). This inventory includes all major sources of emissions originating within DRB boundaries, including diesel and gasoline combustion in motor vehicles and natural gas combustion to heat residential and commercial buildings. It also includes the "upstream" emissions from burning natural gas, coal, and other fossil fuels to produce and transmit electricity to residential, commercial, and industrial accounts within the county boundaries.

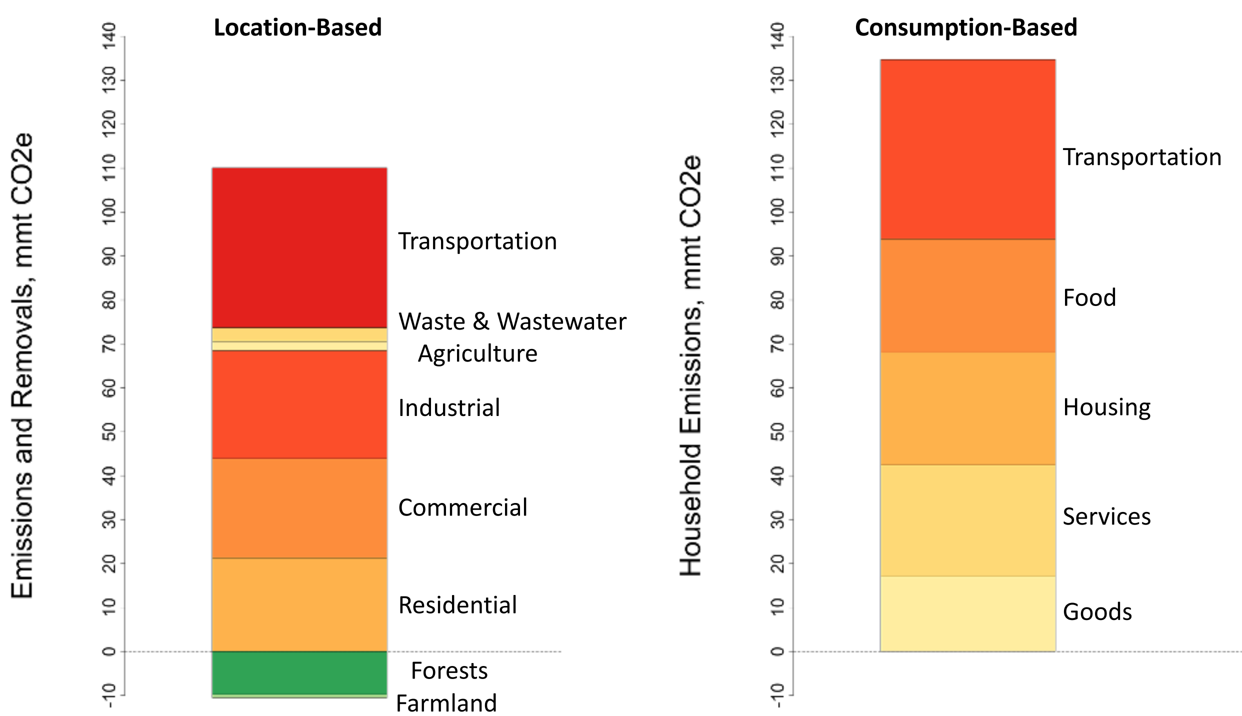
The location-based inventory also includes estimates of carbon-dioxide removals from forests and farmland, where CO_2e is absorbed from growing vegetation through photosynthesis and stored as plant biomass and soil organic carbon.

We also report a 2021 **consumption-based inventory** for households in the DRB. Consumption-based inventories take individual households as the unit of analysis (EcoDataLab, 2023; Jones & Kammen, 2011). This inventory incorporates emissions from electricity or fossil fuel consumption in the home, and it also further estimates the "upstream" emissions of all goods and services consumed by the household. This inventory provides a more comprehensive estimate of household-level climate impacts, taking into account the greenhouse gas pollution involved in growing food, manufacturing consumer goods, and shipping products around global supply chains. Consumption-based inventories do not include direct emissions from businesses and industries that may be located within a community.

Location and consumption-based inventories provide two complementary viewpoints on a community's greenhouse gas emissions. In most U.S. cities and towns, emissions from a consumption inventory will be significantly higher than emissions from a location-based inventory. In these urban communities, there may be relatively few industrial sources of emissions (included in a location-based inventory), while there will be substantial "upstream" emissions required to feed and provision a dense population from farms and businesses outside of the community (included in a consumption-based inventory).

The DRB has a mix of land uses and population densities, with dense urban areas around the Philadelphia, Wilmington, and Allentown metropolitan areas, productive agricultural areas in southeastern Pennsylvania and central Delaware, and more heavily forested areas in the northern watershed. As a result, the location-based and consumption-based inventories are similar in overall emissions (Figure 2). The location-based inventory totaled 110 mmt CO_2e, and the consumption-based inventory totals 135 mmt CO_2e.

Figure 2. Summary of location-based and consumption-based 2021 greenhouse gas inventories for the Delaware River Basin (in million metric tons of carbon dioxide equivalents).



For both inventories, transportation is the largest source of emissions, stemming from the urban and suburban population centers. Industrial emissions from petroleum processing and manufacturing are also a major source of emissions in the location-based inventory. Emissions from commercial and residential buildings make up 39.9% of the location-based inventory, split roughly evenly between electricity emissions and natural gas and other fossil fuels for heating. Direct emissions from agriculture (enteric methane emissions from livestock and nitrous oxide emissions from manures and fertilizer) make up a small portion of the location-based inventory, at 1.9%. Total per-capita emissions are 12.7 t CO_2e per year, which is in line with the national average of 19.1 t CO_2e per year (US EPA, 2023c).

For the consumption-based inventory, emissions related to food production and distribution are the second largest category, at 19.2%. Emissions from housing (heating, cooling, lighting, and powering appliances) contributed 19.0% to this inventory. Emissions tied to spending on other goods (12.7%) and services (18.9%) contribute the remainder of this inventory. The average per-household emissions are 40.9 t CO_2e per year across the DRB, which is similar to the national average of 40.0 t CO_2e per year.

Removals from forests and farmland totaled -11.9 and -0.75 mmt CO_2e per year, respectively, which gives net emissions of 97.4 mmt CO_2e for the location-based inventory. In the next sections, we explore how these removals might be increased with alternative management on forests and farms.

Increasing Carbon Removals from Forests

Our location-based inventory shows that forests in DRB are currently removing a substantial amount of CO_2 each year; forests sequester 11.9 mmt annually of CO_2e, offsetting 10.9% of the region's 2021 greenhouse gas emissions. Given the substantial scale of these removals, it's important to assess trends in forest land cover and explore opportunities for forests to remove more carbon dioxide through improved management.

In this section, we review trends in land cover in the basin and forest area. We then explore opportunities to remove carbon via forests through 1.) managing the total area of forests harvested each year, and 2.) managing harvest techniques practiced on specific forest plots.

Forest Land Cover Trends in the DRB

Forests are the dominant land cover in the basin, covering nearly 1.78 million hectares or 53.3% of the total land area. Forests are not evenly distributed across the basin (Figure 3); forested landscapes are dominant mostly in the ridges and highlands of the northern half of the basin and in the coastal plains of the southeastern border. Forest habitats generally occur as woodland fragments in a mosaic with cropland and pastures.

While forest land cover increased steadily over the second half of the 20th century (mainly due to abandonment of agriculture), this trend has unfortunately reversed over the last two decades. Data from the National Landcover Database (NLCD) shows that there has been a steady reduction in forest area over the period 2001-2019. Over 3.1% of total forest has been lost since 2001, with the biggest losses occurring since 2016 (Figure 4).

Comparing the NLCD maps for 2011 and 2019, we found that forest was mostly transformed into urban (47.1%) and agricultural (31.8%) land uses. There were some areas of reforestation, with new forest growing on land previously classed as agricultural (35.5% of new forests) or shrubland (28.2% of new forests). Extrapolating recent trends into the future, we estimate that by 2100, the basin could lose between 17.0 to 24.4% of forest cover compared to a 2001 baseline. A 2100 worst-case scenario could be 58.7% forest loss if the accelerated loss rates since 2016 continue unabated.

Figure 3. Distribution of forest and agriculture land cover across the DRB. Data from the 2019 NLCD.

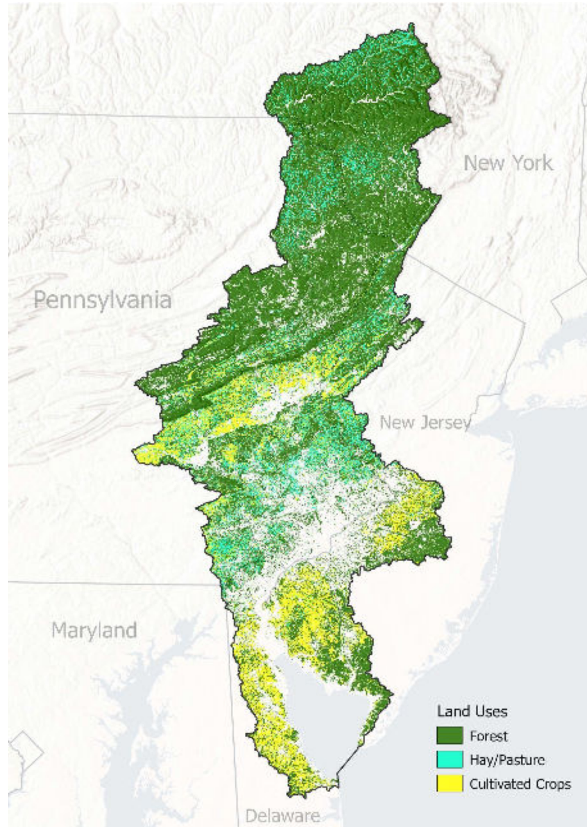
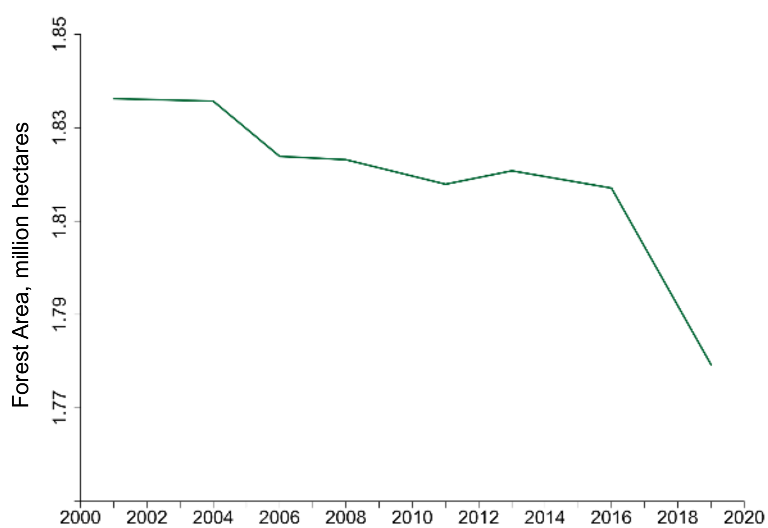


Figure 4. Trends in forest land cover area across the Delaware River Basin, 2001-2019.

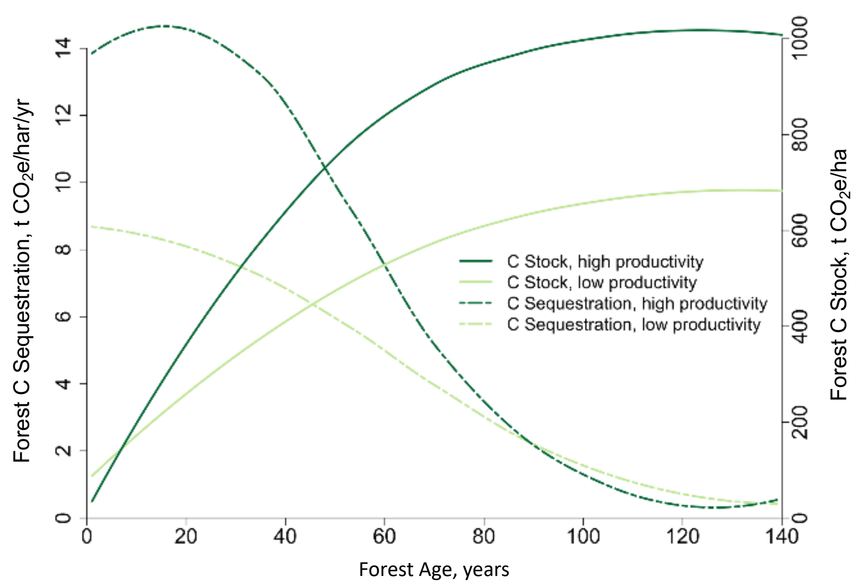


Managing Harvests in Forests across the DRB

Currently, we estimate that on average around 2,060 hectares of forests are harvested for timber products each year in the basin. These areas are not converted to other land uses but are allowed to regenerate after wood products are extracted. Perhaps somewhat counterintuitively, it may be possible to increase carbon removals in the basin by i*ncreasing* the total area harvested each year.

Carbon dynamics in a forest following a harvest event follow a typical pattern (Figure 5). The stock of total carbon in a forest ecosystem hits a low point shortly after harvest, when most above ground carbon has been removed, leaving only dead wood, below ground biomass, and soil carbon. As the forest regrows, total carbon stock steadily accumulates for several decades and then gradually levels off as older trees mature and slow down in their growth rates. Trees grow rapidly over the first 1-2 decades following a harvest, leading to higher rates of carbon sequestration. As the forest matures, annual growth begins to decrease and carbon sequestration trends toward zero after multiple decades. Forests on more productive sites (e.g. more fertile soils) will show higher growth rates than forests on less productive sites, but the general trends of increasing carbon stock and decreasing sequestration rates over time will be similar across sites.

Figure 5. Typical dynamics of carbon stock accumulation and annual carbon sequestration rates in northeastern U.S. forests following a timber harvest event.

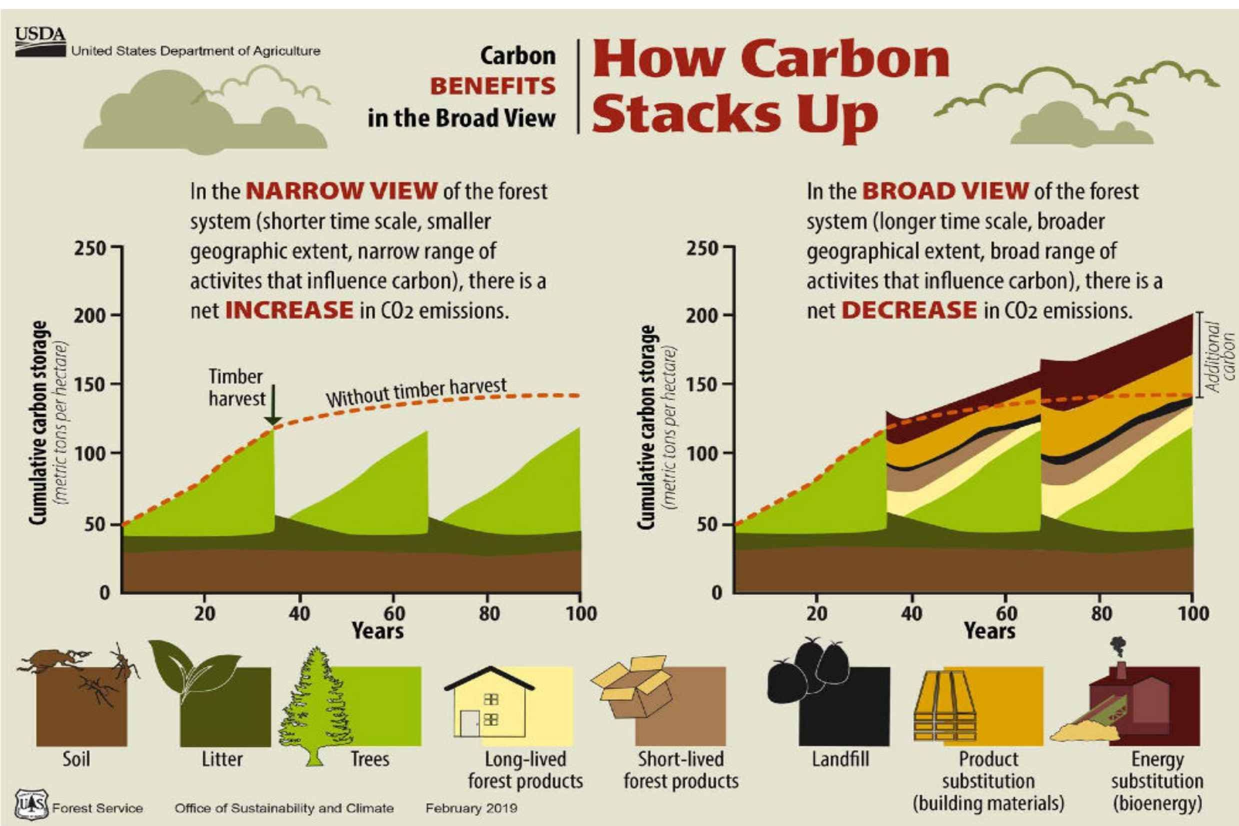


As a result of this general pattern, it's possible that increasing the harvested area of a region could reset more forest towards higher growth and sequestration rates, leading to higher net removals of carbon. To this point, we found that the age distribution of forest in the DRB skews heavily towards more mature forests, with 37.2% over 100 years old. Current forest carbon removals in the DRB reflect the work of a mature age distribution, so it's possible that a younger forest distribution could sequester substantially more carbon.

To assess the effects of increasing harvest area, we developed a forest growth model adapted from the National Forest Carbon Monitoring System (NFCMS) datasets. We developed an "as usual" scenario that takes the annual rate of harvested area observed over the period 2010-2019 and continues this harvest rate each year out to 2100. For each of 9 forest types in the NFCMS, there is a typical rotation timeline for harvest, regeneration, and harvest. To meet the as usual annual harvest rate, we randomly selected 30m x 30m cells within the DRB for each year of the simulation, while excluding cells that had previously been harvested within the rotation period for that forest type. We also excluded any cells located within conservation areas or within 50m of a stream or waterway. We then created an "up 20%" scenario, where the area of cells selected for harvest each year was increased 20%, and a "down 20%" scenario where the harvested area was decreased 20%.

A key assumption in a proposal to increase carbon removals by harvesting more forests rests in the fate of harvested wood products. The carbon in some forest products, like fuel wood, is rapidly returned to the atmosphere as carbon dioxide upon burning. The carbon in other wood products, like high-quality furniture or framing lumber, might be safely stored for decades or longer. The carbon in other wood products like paper or packaging may make its way to a landfill, where a fraction will be stably stored underground and another fraction will be decomposed and released to the atmosphere as CO_2 or methane. If more of harvested wood products are used for stable, long-lived products like framing lumber or engineered wood products, the cycle of forest harvest and regrowth can lead to substantial carbon removals (Figure 6).

Figure 6. Typical pattern of carbon stocks in forests and harvested wood products after a timber harvest. Graphic is reprinted from USDA (2019).



Predicting the fate of harvested wood products in the global economy is incredibly complicated, and end-uses will vary considerably based on the quantity and quality of harvested materials, prices and market conditions, waste management and recycling systems, and many other factors. For a general approximation, ICLEI USA has developed a tool to estimate the 100-year fate of harvested wood products from different subregions of the U.S. (Birdsay & Harris, 2021). We used this tool to estimate that over a 100-year time frame, roughly 33% of the carbon in wood products harvested from Northeast U.S. forests will remain in durable products (e.g., furniture, biochar), while 67% will have been released back to the atmosphere. We use this 33% in stable storage as a rough benchmark for the fate of wood products in our model analysis. We also present results for a 100% stable storage scenario, which might be achieved by encouraging forest managers to focus on species suitable for long-lived wood products. While 100% stable carbon is probably not actually achievable, this set of scenarios allows us to assess the upper bounds of carbon removals achieved through forest harvests.

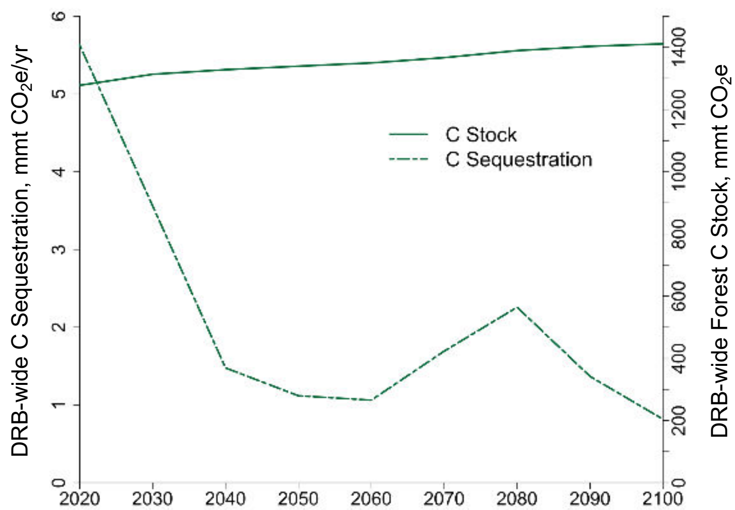
Our analysis shows that a substantial change in harvested area (+/- 20%) has only a small effect on basin-wide carbon stocks and sequestration rates (Table 1). Not surprisingly, increasing total harvested area over the period 2020-2100 can be expected to lead to a net decrease in total forest C stocks, summing all aboveground and belowground C pools. This result indicates that although forest stands may have elevated carbon sequestration rates for decades following harvest, this increase is not sufficient to compensate for the ongoing losses of forest carbon as new stands are harvested year after year. The net loss of forest C from harvests can be partially compensated for by the larger stable C in wood products. However, if we assume 33% stable C in wood products, there is not enough stable C from extracted wood products, and the "down 20%" scenario leads to higher average annual removals. If we assume that all C in wood products is stable, then the "up 20%" shows very slightly higher average annual removals. This result demonstrates that the end-use of wood products has a significant effect on the overall carbon balance of forests in the DRB. Any policies or programs that can encourage long-lived wood products or biochar production from harvested acres can increase net carbon removals from harvested acres.

Table 1. Projected forest C, C in stable wood products, and average annual C removals in the Delaware River Basin under three scenarios of harvested area, 2020-2100.

	% stable C in wood products	As Usual	Up 20%	Down 20%
Total Harvested Area (ha), 2020 to 2100		235,531	287,562	188,328
Change in Forest C (mmt CO2e), 2020 to 2100		133.5	119.3	146.4
Stable C (mmt CO2e) in Harvested Wood Products, through 2100	33%	23.3	28.6	18.6
	100%	70.2	86.3	56.2
Average Removals per Year (mmt CO2e), through 2100	33%	-1.96	-1.85	-2.06
	100%	-2.55	-2.57	-2.53

The trend of steadily aging forests will lead to substantial reductions in forest C sequestration across the basin over the coming decades. In the as usual scenario, our model shows that total C stock in DRB forests will gradually plateau at around 1400 mmt by the end of the century (Figure 7). Annual basin-wide forest C sequestration rates will decline rapidly from around 5.6 mmt CO_2e per year in 2020, and level off at 0.9 mmt CO_2e per year by the end of the century. As a result, C removals from forests will progressively offset a smaller and smaller portion of the DRB's total emissions over the coming decades.

Figure 7. Projected forest C stock and annual forest C sequestration under current annual harvesting in the Delaware River Basin, 2020-2100.



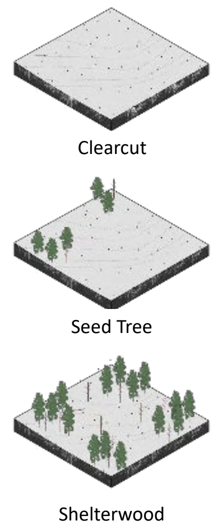
It's important to point out that the average annual removals estimated for the as usual scenario in 2020 (5.6 mmt CO2e) are substantially lower than the annual forest removals included in our location-based inventory (11.9 mmt CO2e). For our location-based inventory, we used a tool developed by ICLEI USA, because this approach is the most commonly used tool for local and regional greenhouse gas accounting in the U.S. and makes our results more comparable with other communities. The ICLEI model is appropriate for a general estimate, but it calculates forest C sequestration using a limited set of average rates for just three forest age classes per forest type. For our analysis of sequestration dynamics after harvest, we needed a much more fine-grained modeling tool. The discrepancy between our model estimates can mainly be attributed to different sequestration estimates for mature forests over 100 years old; ICLEI estimates that common Northeast forest types will still have sequestration rates of 3.4-5.4 t CO_2e per hectare per year after 100 years, while our model predicts that sequestration will level off to around 0.5 t CO_2e per hectare per year by this maturity. These contrasting estimates underscore that estimating forest C dynamics is inherently difficult and imprecise.

Managing Harvests in Individual Forest Stands

In addition to adjusting the total area of harvested forests, the specific harvest techniques practiced in a given forest stand can also affect carbon sequestration rates and the (re)-accumulation of carbon stock.

There are several common forestry techniques that are used for timber harvest which leave different numbers of trees remaining after the harvesting treatment, in different spatial arrangements (Figure 8). **Clearcutting** typically removes all trees in a given area—although the size and shape of a clearcut can vary based on management goals. **Seed tree** cutting leaves a few of the best trees uncut, so that they can act as seed sources for the regeneration of the stand. **Shelterwood** cutting typically leaves larger patches of uncut forest until new seedlings become established.

Figure 8. Examples of distribution of trees following clearcut, seed tree, and shelterwood harvest techniques.



Established forest management laws and common harvesting practices vary across the states in the DRB. Delaware promotes a seed tree law where 6-8 trees greater than 14 inches diameter need to be left as residual trees per acre (Delaware Forest Service Department of Agriculture, 2022). New Jersey's seed tree law requires 7-12 residual trees per acre be left on site, and that all dead snags of 10 inches diameter and 6 inches in height be left standing (New Jersey Government Pinelands Forestry Advisory Committee, 2006). Pennsylvania accepts clearcutting as a regeneration practice but doesn't have explicit limits on seed tree or shelterwood practices, while New York promotes various practices depending on stand age and health. These are general guidelines, and the number of residual trees would vary depending on stand age, density, and basal area, leading to quite a large degree of variability. These laws and guidelines have typically been designed for the commercial, biodiversity, and soil and water benefits of healthy forest regeneration, rather than explicitly intended for carbon sequestration.

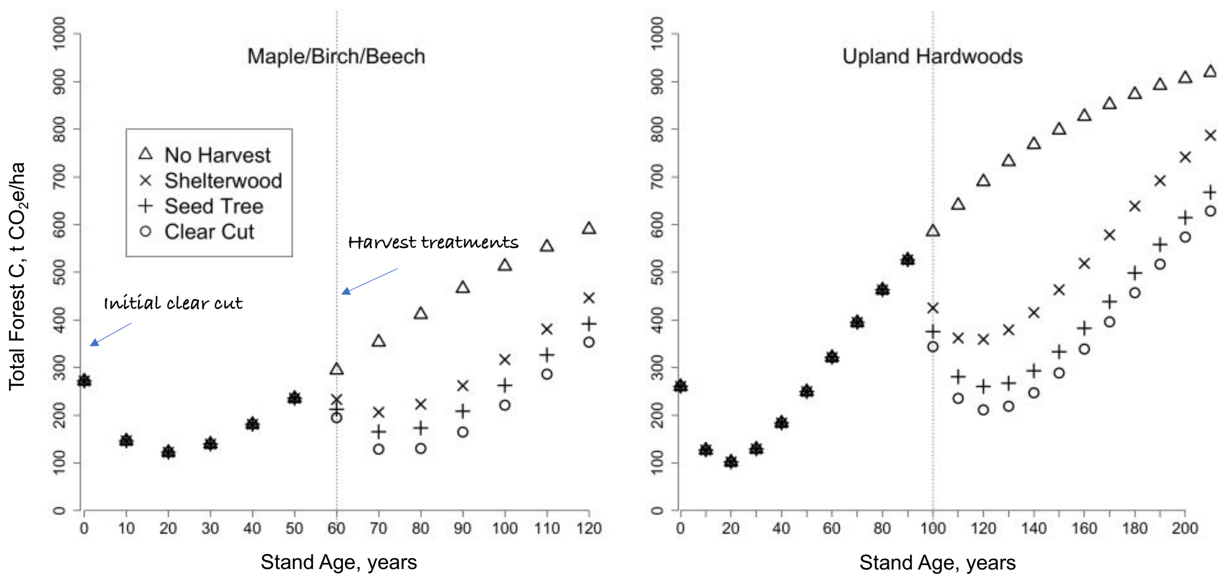
To see how large the difference in carbon stocks and sequestration rates might be when comparing clearcut harvesting to other typical forest management approaches, we used the U.S. Forest Service's Forest Vegetation Simulator (FVS) tool to simulate forest carbon over time across clearcut, seed tree, and shelterwood harvest techniques. The FVS model returns estimates for total carbon in aboveground and belowground biomass, but it does not include soil organic carbon. However, the relative differences in estimated forest C across harvest techniques are likely to be consistent with or without soil organic carbon.

We compared these harvest techniques for the two most abundant forest types in the DRB: maple/beech/birch (44% of 2019 forest area) and mixed upland hardwoods (25% of forest area). For each forest type, we ran the FVS model on 10 randomly selected plots within the DRB for a total of two rotation periods. In the Northeast U.S., maple/beech/birch forests are typically harvested on a 60-year rotation (Martin & Lorimer, 1996; Leak et al. 2014) while upland hardwood forests are typically harvested on a 100-year rotation (Guyette et al. 2006; Leak et al. 2017). For each forest type, we ran the

FVS model for one rotation period following an initial clearcut simulation and then for one rotation period following a no harvest, shelterwood, or clearcut treatment.

The FVS model shows that forest carbon levels drop precipitously after a harvest operation and begin to recover 20-30 years afterwards (Figure 9). For both forest types, we found that forest C stocks recover faster following harvests for shelterwood and seed tree methods than for clearcuts. For both forest types, we found that the no harvest treatment continues to steadily accumulate C and only begins to reach a C stock plateau towards the end of the 2nd rotation period. As a result, none of the three harvest treatments are able to "catch up" and compensate for the C lost during and after harvest operations. Because of the longer rotation period, the C difference between harvested and no harvest treatments was smaller at the end of the rotation for upland hardwood stands than for maple/birch/beech stands.

Figure 9. Total forest C in maple/birch/beech and upland hardwood forest stands following no harvest, clearcut, seed tree, and shelterwood harvest treatments. Each data point is the mean of 10 stands modeled in the Forest Vegetation Simulator.



Averaged over the entire rotation period, annual C sequestration rates are greater for the no harvest treatments than for any of the harvested treatments, for both forest types (Figure 10).

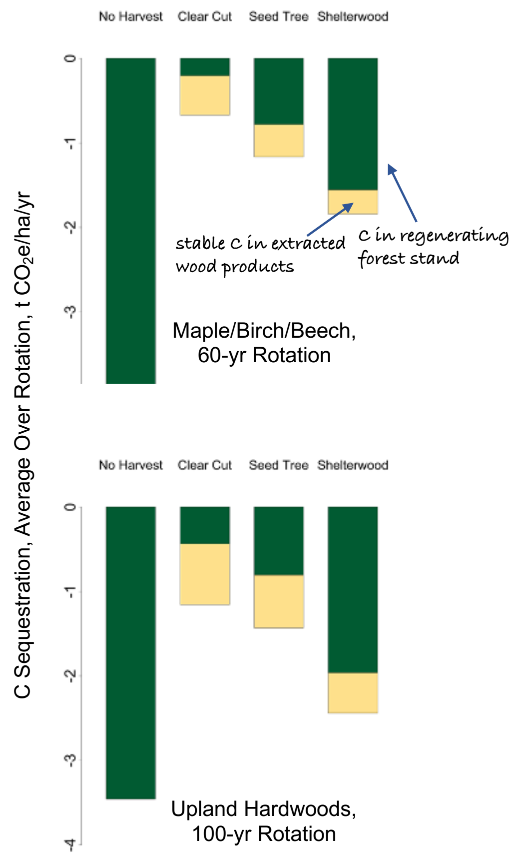
Carbon losses after harvest can be partially compensated if some of the C in harvested wood is stored in durable wood products, assuming a 33% 100-yr stability of harvested wood products (Birdsay & Harris, 2021).

For the maple/birch/beech stands, the seed tree and shelterwood treatments show average annual carbon sequestration rates 74.0% and 176% greater than clearcut, respectively.

For upland hardwood stands, the seed tree and shelterwood treatments show average annual carbon sequestration rates 23.9% and 111% greater than clearcut, respectively.

These results highlight that the rotation period of managed forests can have a significant effect on C sequestration dynamics. Working forests are often harvested decades before C stock has plateaued because the economic value of harvested wood products reaches an optimum before C stock reaches a stable plateau. The shorter-term economic cycle makes it challenging for regenerating forests to compensate for carbon losses following harvests, even when accounting for some C storage in stable wood products. Managing harvest cycles to maximize C sequestration would require balancing incentives from the value of wood products against the social or economic value of additional C sequestration.

Figure 10. Annual C Sequestration in maple/birch/beech and upland hardwood forest stands following no harvest, clearcut, seed tree, and shelterwood harvest treatments.



These results also suggest that encouraging shelterwood and seed tree practices over clearcuts on working forests could be helpful for increasing carbon removals in the DRB. However, while these techniques probably increase stand-level carbon removals relative to clearcut practices, it is not clear how much of an impact they would have over the watershed scale. DeLyser et al. (2022) reported that most Pennsylvania forests are already harvested using shelterwood or seed tree practices, and clearcuts are only practiced on 3.1% of harvested stands. And as we showed in the section above, significant increases in the area of harvested forest had relatively minor effects on basin-wide carbon dynamics.

Increasing Carbon Removals from Farmland

Globally, an enormous amount of carbon is stored in the soils of terrestrial ecosystems. For soils under agricultural production (cropland and pastures), soil organic carbon levels are typically significantly lower than soils under native grassland or forest ecosystems in the same region. Large amounts of soil organic carbon are typically emitted from soils during the initial decades of land clearing, soil disturbance, and cultivation. As a result, the soils under most farm fields and pastures currently only store a fraction of their potential organic carbon capacity.

Farmers and agricultural scientists have made tremendous progress over recent decades developing farming systems that can rebuild and restore soil organic matter and soil health, often under the banner of "regenerative agriculture." Regenerative agriculture practitioners embrace a wide range of tools and techniques, but they typically include the elements of 1. keeping soil covered, 2. maintaining year-round living roots, 3. minimizing soil disturbance, 4. increasing crop diversity, and 5. integrating livestock. Globally, Project Drawdown (Hawken, 2017) estimates that regenerative farming practices could help sequester 41.7 billion metric tons of CO_2e each year, or 4.0% of annual global human-caused greenhouse gas emissions.

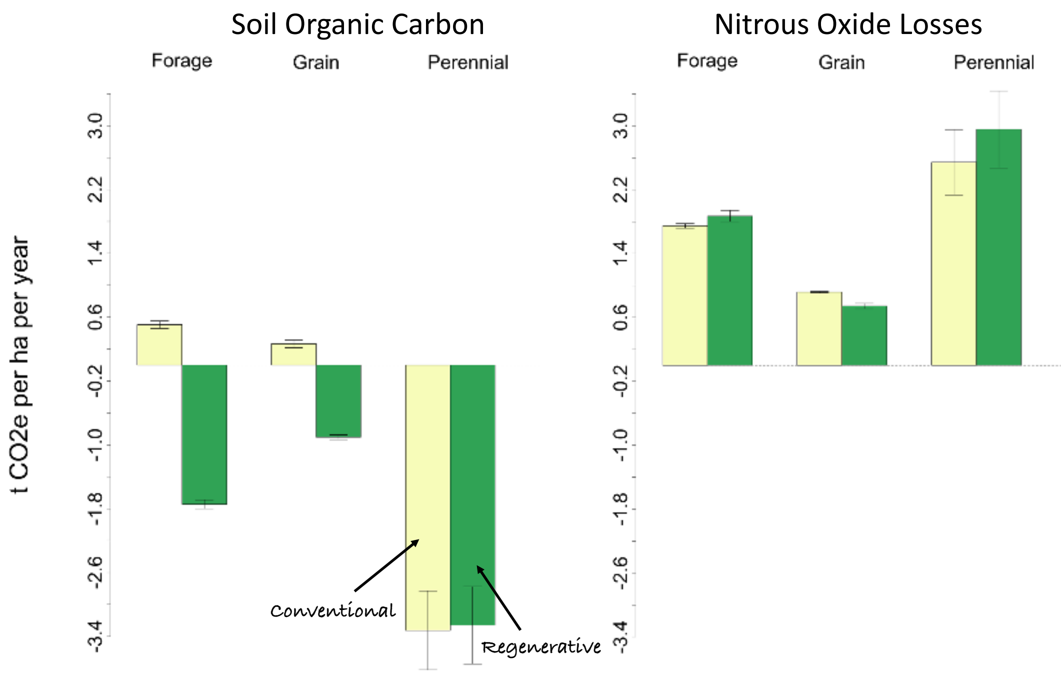
More locally, how much more carbon could farmers in the DRB sequester each year with regenerative ag practices? To get at this question, we used the USDA COMET-Farm model to simulate carbon and nitrogen cycling in the farming systems that are typical for the region. We used statistics from the U.S. Census of Agriculture and other sources to describe conventional practices for forage crops grown for a dairy farm, cash grain crops, and perennial hay production. We then described regenerative farming systems based on regional trends and innovations in sustainable and regenerative farming practices. The regenerative systems feature a transition to no-till production, integrating cover crops and additional cash crops, and reducing quantities of manure and nitrogen fertilizers (Table 2).

Table 2. Summary of conventional and regenerative practices modeled for forage, grain, and perennial hay cropping systems. UAN is urea-ammonium-nitrate fertilizer.

	Conventional	Regenerative
Forage	3 yr corn silage, 3 yr alfafa intensive tillage liquid dairy manure	3 yr corn silage-ryelage, 3yr alfalfa no-tillage reduced manure in corn
Grain	corn grain - soy intensive tillage UAN fertilzer	corn grain-rye, soybean-wheat, wheat -rye/vetch no-tillage reduced UAN fertilzer in corn
Perennial	continuous grass hay no-tillage UAN fertilzer	continuous grass hay no-tillage UAN fertilzer

We found significant improvements in soil carbon sequestration with regenerative practices for forage and cropping systems (Figure 11). For forage systems, the transition to no-till and the addition of a ryelage winter annual crop helped lead to a shift from 0.51 t CO_2e per hectare per year emissions to -1.74 t CO_2e per hectare per year removals. For grain systems, the transition to no-till and the addition of winter wheat and winter cover crops lead to a shift from 0.27 t CO_2e per hectare per year emissions to -0.90 t CO_2e per hectare per year removals. For the perennial hay system, the regenerative system is similar to the conventional system because hay production already has very low soil disturbance and year-round living roots. Soil carbon sequestration actually decreases in the perennial regenerative system compared to the conventional (-3.33 to -3.26 t CO_2e per hectare per year). For perennial hay, the regenerative system was simply modeled as a continuation of the conventional practices, and the COMET model shows soil organic carbon stocks becoming more saturated over time, such that sequestration per year decreases.

Figure 11. Soil organic carbon sequestration and nitrous oxide losses for typical cropping systems in the Delaware River Basin, simulated using the COMET-Farm model.



All agroecosystems have some emissions of nitrous oxide from fertilizers and manures. Crop and pasture plants are typically not able to capture and utilize all the nitrogen applied as manure, compost, or synthetic fertilizer. A significant fraction of the unutilized nitrogen gets converted into nitrous oxide by soil microbes and released to the atmosphere. Nitrous oxide is a potent greenhouse gas, with a 100-year global warming potential 264 times that of carbon dioxide (US EPA 2023e).

Our model results indicated that these cropping systems had substantial nitrous oxide emissions and that emissions could be slightly greater under regenerative management in some cropping systems. In the forage and grain rotations, the addition of cover crops helped to reduce the amount of fertilizer needed in subsequent corn cash crops. But, the addition of new cash crops to the rotation (ryleage for the forage rotation, winter wheat for the grain system) meant that farmers were adding fertilizers and manure at more points in the rotation. Especially for the forage rotation, nitrous oxide emissions could counteract potential benefits from increased soil organic carbon sequestration.

Figure 11 shows carbon and nitrous oxide flows per unit area, but how do these rates translate to the watershed scale? We used statistics from the NLCD and U.S. Census of Agriculture to estimate the total land area over which the forage, grain, and hay production systems are likely to be practiced. Totaled over the DRB, we found that farmers could sequester -0.75 to -1.38 mmt CO_2e per year, under conventional or regenerative ag scenarios, respectively, or just 0.7 to 1.3% of the total location-based inventory emissions (Table 3).

Table 3. Greenhouse gas emissions and removals from agriculture and farmland soils across the Delaware River Basin under Conventional and Regenerative Cropping systems. Values are in units of mmt CO_2e (million metric tons carbon dioxide equivalents) per year.

	Conventional	Regenerative	Net Change
Enteric CH_4	0.63		0
Manure Storage	0.29		0
Soil N_2O Losses	1.18	1.30	0.12
Soil Organic C	-0.75	-1.38	-0.63
Total	1.35	-0.08	-0.51

This is a substantial difference from the 4.0% of global emissions that Project Drawdown estimates suggest could be offset worldwide by regenerative farming practices. Much of this discrepancy can be explained by the fact that the DBR has a large population (8.61 million people) and relatively little farmland (0.62 million hectares). It's also possible that further refinements in regenerative ag practices could lead to higher rates of sequestration and that the COMET model does fully capture the synergistic possibilities of combining reduced tillage, crop diversity, perennial cover, and other innovations in regenerative agriculture.

Still, even if soil organic carbon sequestration rates could be doubled or even tripled, this increase would have little effect on the bottom-line reality that farmland soils play a small part in the local DRB greenhouse gas budget. It's also important to note that removals from farmland soils are smaller than emissions from other ag sources (Table 3), including enteric methane and nitrous oxides. Focusing climate outreach and implementation efforts on helping farmers switch from beef and dairy production to other products or reducing nitrous oxide emissions could have greater greenhouse gas benefits than a focus on soil carbon.

Land Use Alternatives and Climate Action in the DRB

Our analysis shows that forests currently remove a significant portion (10.8%) of the DRB's annual location-based greenhouse gas emissions while farmland removes only around 0.7%. Our modeling analysis indicates that large-scale changes in management practices would have very modest impacts on forest carbon stocks or farmland sequestration rates. Yet despite these small effects on per-hectare removal rates, land use decisions for forests and farmland can have enormous implications for the greenhouse gas inventory of the DRB. To see the importance of forests and farmland for greenhouse gas emissions, it's important to compare greenhouse gas balances from forests and farmland to alternative land use choices.

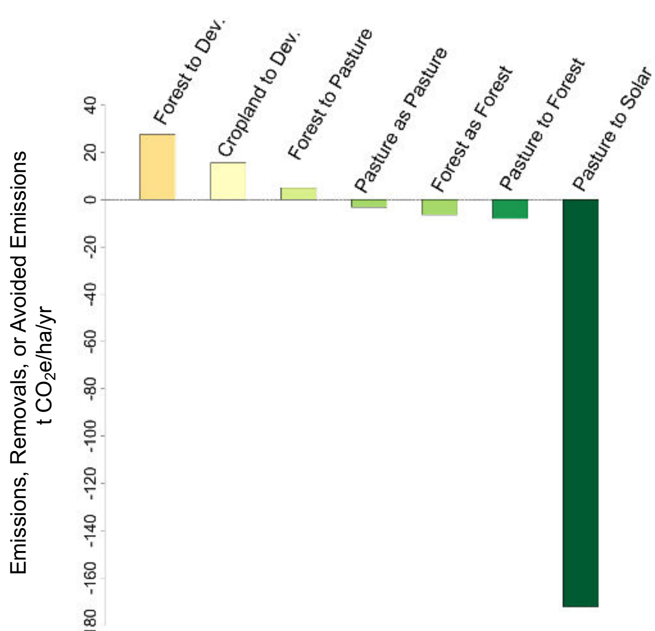
As a basin-wide benchmark, our analysis using the ICLEI-LEARN tool (Birdsay & Harris, 2021) indicates that mature forests remove around 6.42 t CO_2e per hectare per year, while new forests planted to retired pastures or cropland can remove around 7.99 t CO_2e per hectare per year. Conversely, any land use decision that converts forest to farmland, or forest to development, will release significant amounts of carbon dioxide in the first year, when standing vegetation is cleared and soil is disturbed to make way for crops or housing. Averaged over a 20-year period, this one-time release of forest carbon emits 12.0 t CO_2e per hectare, as a basin-wide average.

Clearing forests or farmlands for new low-density housing developments brings even more greenhouse gas emissions into the watershed. Households in new low-density developments have substantially higher annual emissions compared to new housing within existing towns and settlements. The added emissions come from longer commutes and more drive time, greater energy use to heat and power bigger houses, and soil disturbance from new construction. In a case study of suburban sprawl in suburban Illinois, researchers at the American Farmland Trust (McGill et al. 2022) found that new suburban development brings an additional 15.6 t CO_2e per hectare per year.

Taking both forest carbon loss and additional household emissions, forest conversion adds emissions of 27.6 t CO_2e per hectare per year (Figure 12). **These estimates underscore the critical importance of open space preservation, land use planning, and smart growth for local climate action.**

Interestingly, farmland solar may be among the most positive land use options, from a climate perspective. These arrays can produce around 562 MWhr of electricity, per hectare, per year, according to a national benchmark provided by the National Renewable Energy Laboratory (NREL, 2013). The solar-generated electricity displaces power that would have been generated on the regional utility grid, which is mainly fueled by natural gas and some coal. Farmland solar therefore leads to about 172 t of avoided CO_2e per hectare, per year. Based on these values, if the DRB dedicated around 1/3 of its pastureland to farmland solar it could offset all of its electricity use in residential buildings.

Figure 12. Annual per hectare greenhouse gas emissions (t CO_2e) or removals and avoided emissions from alternative land uses in the Delaware River Basin.



Solar power generation does not necessarily need to come at the loss of farmland, or even to compete with food production. Solar panels can be removed and decommissioned, and farmers can return the land to alternative agricultural uses at the end of a lease (PA PUC, 2019). Farmers are also refining a range of agrivoltaic systems, including grazing livestock between and underneath panels or growing specialty crops under elevated panels. Sheep, for instance, appear to be well-suited to solar grazing systems. The livestock provide a second income stream for farmers, while also reducing maintenance costs from mowing (Hartman, 2023). Sheep also produce substantially less enteric methane than beef cattle (Ritchie & Roser, 2021). Across the DRB, where much of the pastures and hay crops are used to support beef and dairy cattle, a transition to solar sheep grazing could also bring a reduction in enteric methane emissions.

Through the DRWI, the William Penn Foundation has identified a set of 19,685 unique Opportunity Parcel areas that are priority locations for land preservation and stewardship projects. In 2020, the Opportunity Parcels were distributed across annual cropland, pastureland, and forest land uses. Table 4 shows a land use transition matrix showing the greenhouse gas emissions or removals implications of transitioning *all* of the land in Opportunity Parcels to developed, cropland, pasture, forest, or farmland solar land uses. These estimates present an upper bound - it's both unlikely and undesirable that all of the Opportunity Parcels will be transitioned to solar over coming decades. Still, these estimates demonstrate there is likely more than enough land resource in the Opportunity Parcels alone to offset the DRB's emissions with renewable energy generation. Conversely, if the Opportunity Parcels are lost to development, we could see more than a 20% increase in greenhouse gas emissions.

Table 4. Upper bound estimated greenhouse gas emissions and removals (mmt CO_2e per year) resulting from hypothetical land cover transitions in the Delaware River Watershed Initiatives "Opportunity Parcels".

From:	To: Developed	Cropland	Pasture	Forest	Solar
Cropland (217,453 ha)	3.39	-0.30	-0.71	-1.74	-37.4
Pasture (150,297 ha)	2.34	-0.21	-0.49	-1.20	-25.9
Forest (628,615 ha)	17.4	5.07	3.15	-4.04	-103.2

Conclusions and Next Steps

Our analysis shows that communities and businesses in the DRB contribute a substantial amount of greenhouse gas pollution. The DRB contributes nearly 1.7% of total U.S. emissions, so climate action in this region has significant implications for setting the nation and globe on a sustainable climate path.

Natural lands, especially forests, offset a significant amount of these emissions through carbon removals. However, improved management in these lands may have limited potential to increase these removals.

Substantially decreasing the area of harvested forest area led to a 5.7% increase in net carbon removals from forests over the period 2020-2100. However, this result rests on assumption of 33% stable C in harvest wood products. If 100% of the carbon in wood products could be directed towards long-lived products, then increasing harvested area would have a slight improvement over the as usual harvested area scenarios. For forests that are harvested, shifting to seed tree and shelterwood practices could enhance carbon by 0.28 to 1.28 t CO_2e per hectare per year, averaged over a 60- or 100-year harvest rotation. Overall, forests are aging in the region, and we can expect annual removals across the watershed to steadily decline over the next 80 years.

On individual fields and farms, regenerative ag practices can substantially increase C removals. However, these gains in soil organic carbon can be largely counteracted by increases in nitrous oxide emissions if fertilizer and manure applications are not also carefully managed. At the watershed scale, a widespread adoption of regenerative ag practices would only increase C removals by 0.63 mmt CO_2e per year, or just 0.6% of total greenhouse gas emissions in the DRB. Improving nutrient management practices or developing alternative enterprises to dairy and beef (which have substantial methane emissions) may be a more direct way to mitigate climate emissions from agriculture.

Preserving existing natural lands emerges as a key priority for all climate action; while forests and farmland clearly cannot offset the DRB's contribution to climate change, the loss of these resources would lead to a substantial increase in regional emissions. Through protecting existing forests and farmland, there may be opportunities for multiple benefits. For instance, if forest conservation is conducted in concert with local land use planning that encourages housing development within developed areas, conservation retains forests carbon removals while also limiting emissions from housing and transportation. Agrivoltaic projects on farmland can supply zero-emission electricity to the regional grid while also producing sheep, vegetables, and other products that have lower life-cycle emissions than beef and dairy.

Moving forward, we recommend the William Penn Foundation orient its climate work around preserving and protecting natural lands in the Opportunity Parcels and throughout the DRB, while supporting efforts that responsibly integrate solar energy production on farmland.

Technical Methods

Greenhouse Gas Inventories

Location-Based Inventory

We developed our location-based inventory using the framework provided by the ICLEI Community Protocol (ICLEI USA, 2019), with details and modifications explained below.

Transportation: we estimated emissions from transportation using the National Renewable Energy Laboratories SLOPE tool (NREL, 2023). We used the "Scenario Planner" view and calculated emissions for the "reference scenario" for a 2021 baseline for all counties within the watershed. For counties that span watershed boundaries, we allocated total county transportation emissions to the DRB based on the proportion of developed land area within the watershed, calculated using the 2019 National Land Cover Database. The SLOPE tool returns CO_2 emissions for diesel and gasoline vehicles as well as emissions from electricity generation for electric vehicles.

Industry: we estimated emissions from industrial operations using the National Renewable Energy Laboratories State and Local Planning for Energy (SLOPE) tool (NREL, 2023). We used the "Scenario Planner" view and calculated emissions for the "reference scenario" for a 2021 baseline for all counties within the watershed. For counties that span watershed boundaries, we allocated total county industry emissions to the DRB based on the proportion of developed land area within the watershed, calculated using the 2019 National Land Cover Database. The SLOPE tool returns CO_2 emissions from electricity consumption (accounting for fossil fuel energy used to produce the electricity) and natural gas combustion at industrial sites. For industrial uses, the SLOPE model does not include emissions from combustion of other fossil fuels, including coal, oil, or other petroleum fuels. We estimated emissions from these fuels using statistics from the U.S. Department of Energy 2018 Industrial Energy Data Book (NREL, 2019).

Estimates from the Industrial Energy Data Book can be broken down by NAICS (North American Industry Classification System) types, which include mining, manufacturing, construction, and agriculture. For agriculture, industry emissions include fuel used to power farm equipment and fuels and electricity for processing facilities and outbuildings. Emissions from animals, manures, and soils are included separately in the agriculture section of this inventory.

Industrial operations that emit more than 15,000 t of CO_2e are required to report emissions directly to the U.S. EPA Greenhouse Gas Reporting Program (GHGRP). Emissions from fossil fuel combustion in the GHGRP for these major emitters overlaps with Industry estimates from the SLOPE model, so we did not separately include the major emitters for fossil fuel combustion. Emissions from power plants are typically reported to the GHGRP, but we accounted for these separately as the electricity consumed by residential, commercial, and industrial accounts. The DRB also has multiple industries that emit significant fugitive emissions, including methane from petroleum processing and PFC and SF_6 from electronics manufacturing (US EPA, 2023b). For major emitters reporting to the GHGRP, these emissions were included as a separate line item in the industry section.

Residential and Commercial Buildings: we estimated emissions from residential and commercial buildings using the National Renewable Energy Laboratories SLOPE tool (NREL, 2023). We used the "Scenario Planner" view and calculated emissions for the "reference scenario" for a 2021 baseline for all counties in the watershed. For counties that span watershed boundaries, we allocated total county residential and commercial emissions to the DRB based on the proportion of developed land area within the watershed, calculated using the 2019 National Land Cover Database. The SLOPE tool returns CO_2 emissions from electricity consumption (accounting for fossil fuel energy used to produce the electricity) and combined emissions from combustion of natural gas and other fossil fuels.

Agriculture: All livestock—especially ruminant animals including cattle, goats, and sheep—generate methane as they digest plant matter from their diets. We obtained statistics on the number of beef cattle, dairy cattle, sheep, goats, pigs, horses, and donkeys from all counties from the 2017 U.S. Census of Agriculture (NASS, 2019). For counties that span the watershed boundaries, we allocated animal numbers to the DRB based on the proportional area in pasture or cropland within the DRB, calculated using the 2019 National Land Cover Database. We then estimated per animal, per year enteric methane fermentation using emission factors published in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (US EPA 2023d).

Methane and nitrous oxide are released to the atmosphere as microbes break down manure stored in barns, pastures, and storage equipment. We estimated methane and nitrous oxide emissions from manure using statistics on animal numbers for various livestock classes from the 2017 U.S. Census of Agriculture (NASS, 2019) and statistics on the variety and proportion of different manure storage equipment types from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (US EPA 2023d). We then calculated emissions for each livestock type for each manure storage facility type using equations provided in the U.S. EPA State Inventory Tool (US EPA 2023h).

Nitrous oxide is also released from crop fields and pastures after farmers apply manure and fertilizers. Crop and pasture plants are typically not able to capture and utilize all the nitrogen applied as manure, compost, or synthetic fertilizer. A significant fraction of the unutilized nitrogen gets converted into nitrous oxide by soil microbes and released to the atmosphere. Nitrous oxide is a potent greenhouse gas, with a 100-year global warming potential 264x that of carbon dioxide (US EPA 2023e).

We estimated nitrous oxide emissions from DRB farmland using the Natural Resource Conservation Service's COMET-Farm model (NRCS, 2023). We used statistics from the 2017 U.S. Census of Agriculture (NASS, 2019), the USDA Cropland Data Layer (NASS, 2023), and the Penn State Agronomy Guide (Duiker, 2022) to define crop management practices for typical ("conventional") forage crop, cash grain, and perennial hay production rotations in the DRB. We then ran the COMET-Farm model for these crop management systems on 60 randomly selected agricultural fields from common soil types in the DRB. COMET returns estimates of annual nitrous oxide emissions per unit area. We scaled these per unit area estimates to the entire county based on land use statistics for acreage planted to corn, alfalfa hay, other hay, and pastureland derived from the USDA Cropland Data Layer (NASS, 2023). Additional details on COMET-farm analysis are provided in the Increasing Carbon Removals from Farmland methods section (pgs. 26-27).

Waste and wastewater: we used the GHGRP database to find landfills located within the DRB. We summed total non-biogenic greenhouse gas emissions, which includes methane generated and released to the atmosphere, as well as carbon dioxide emissions from fossil fuel combustion in the landfill facilities. We used the U.S. EPA State Inventory Tool (US EPA, 2023j) to estimate emissions from wastewater for all zip codes in the DRB, based on 2021 population totals from the U.S. Census, allocated population for zip codes that span the watershed based on land area under development.

Land-Based Removals: For forests, we used emission factors from the ICLEI LEARN tool to calculate carbon dioxide emissions or removals per hectare, per year for each forest transition type (Birdsay & Harris, 2021). For farmland, we estimated carbon dioxide removals from cropland and pastureland using the Natural Resources Conservation Service's COMET-Farm model (NRCS, 2023). We parameterized the model for continuous hay and corn silage-alfalfa production as described in the section above for nitrous oxide emissions from agricultural soils.

Consumption-Based Inventory

We calculated our consumption-based inventory using a proprietary dataset licensed by EcoDataLab, a private company affiliated with the University of California's Cool Climate Network (EcoDataLab, 2023). The dataset summarizes household-level emissions for five consumption categories: transportation, housing, food, goods, and services. Emissions estimates for each category are derived based on statistics for activities and spending patterns compiled from a variety of household-level surveys and reports, including the Consumer Expenditures Survey, the National Household Travel Survey, and the Residential Energy Consumption Survey. A detailed description of EcoDataLab's methodology is available at www.ecodatalab.com.

For this report, we summarized 2021 household level estimates across consumption categories for all U.S. Census Bureau census tracts within the DRB. For Census tracts that span the watershed boundaries, we allocated emissions based on an estimate of the proportion of population within the watershed.

Managing Harvests in Forests across the DRB

We assessed the implications of increasing forest harvest across the basin using a spatially explicit model based on methodology developed by the National Forest Carbon Monitoring System. Our model process involves three main steps: 1.) identifying current land cover and annual extent of forest harvest; 2.) fitting regression curves relating forest age to forest carbon using plot-level data; and 3.) summing these curves over the entire basin, under scenarios of current, increased, and decreased annual harvested area. Table 5 summarizes data inputs and sources for each step of our model.

Identifying Current Land Cover and Harvest Extent

We defined the current extent of forest in the DRB using the National Land Cover Database maps for 2011-2019. Within the forested area for this time period, we identified areas of significant forest disturbance using the Landscape Monitoring System (LMS), which uses satellite images to identify areas where forest biomass has decreased. Forest disturbances that occur over a short period of time are defined by the LMS as areas of "fast forest loss." We used the annual extent of fast forest loss areas as a proxy to estimate a baseline of current annual harvest area. This rate was 2,058 hectare per year over the period 1985-2020.

Fitting Regression Curves Relating Forest Age to Forest Carbon

We developed regression curves to quantify the relationship between forest age and living forest carbon (above ground and below ground pools) using plot-level data from the U.S. Forest Service Forest Inventory and Analysis (FIA) program. The FIA database includes measurements from over 355,000 U.S. forest plots, including forest age, forest type, species composition, site productivity (low or high soil fertility) as well as estimates of above- and below-ground biomass. From the FIA database, we selected all plots from the Northeast region that were not disturbed by fire or pest. We tested four possible curve functions (power law, Gompertz, logistic, and Michaelis-Menten), and selected the function with lowest mean standard error for each site productivity-by-forest type combination.

We then scaled these estimates of total living carbon into estimates of total forest carbon (including living and non-living pools) using coefficients which are also a function of forest age. We estimated these coefficients by regressing non-living carbon against living carbon using an exponential decay function. We fit a separate exponential decay function for each forest type and site-productivity combination using data reported in the National Forest Carbon Monitoring System.

Summing Curves Over the DRB

We next used these age-carbon regression curves to project forest carbon stocks from 2020 through 2100 under three harvest scenarios (as usual, increased 20% and decreased 20%). For all cells [30m x 30m] within the DRB identified as forest in 2019 under the NLCD maps, we estimated the current forest age using maps generated by the National Forest Carbon Monitoring System. We then applied the age-carbon curves to each cell, projecting the carbon in each cell in each year moving forward and summing over all forest cells within the DRB.

We simulated harvests within the DRB by randomly selecting forest cells within the DRB in each year of the model simulation (2020-2100) and then resetting the forest age for that cell to zero. We set aside certain cells as inappropriate for harvest, including any forest cells within designated protected areas and cells within 50m of a stream or waterway. For each forest type we defined a recommended rotation based on U.S. Forest Service and forest industry recommendations (Burril et al., 2019; Guyette et al., 2006; Lancaster & Leak, 1978; Martin & Lorimer, 1996a-b; Martin & Lorimer, 1997a-c; Leak et al., 2014; Leak et al. 2017; Univ. of Tennessee, 2005). Once a cell was selected for harvest, we constrained the model not to select that cell again until the forest matured through the entire rotation period.

At the time of harvest, we used our age-carbon regressions curve to estimate total aboveground carbon. As a simplifying assumption, we assumed that 100% of this aboveground biomass could be used for various forest products. We then summed this carbon in harvested wood products over the basin in each model year. We then compared our model results for two sub-scenarios, assuming that either 33% or 100% of carbon in harvested products would be stable over a 100-year time horizon.

Managing Harvests in Individual Forest Stands

We selected forest plots for the Forest Vegetation Simulator (FVS) using the U.S. Forest Service's FIA dataset. We first extracted all forest stands from the FIA database from Pennsylvania, Delaware, New Jersey, and New York within the DRB. We then selected a random sample of 10 stands and ran a test simulation of forest growth, and then selected a second random sample of 10 additional stands for cross-validation. We found that while both samples showed large variation (coefficient of variance), mean values for both samples were similar. This result indicates that a sample of 10 stands can capture a representative mean of forest stands across the basin, but that there is considerable variation of outcomes in individual plots.

Table 5. Summary of data inputs and sources for our model of projected forest C in the Delaware River Basin.

Input	Data Type	Source	Citation
Forest cover, 2019.	30m*30m raster map for entire DRB	National Land Cover Database	Dewitz and USGS, 2021
Harvest frequency, 1985-2022	30m*30m raster map for entire DRB	Landscape Change Monitoring System	USDA Forest Service, 2023
Forest age (as of 2020) Forest type Site productivity	30m*30m raster map for entire DRB	National Forest Carbon Monitoring System	Williams et al., 2020
Forest age, type, and site productivity Forest living biomass Forest living:dead biomass coefficients.	Plot level data tables used to build age-biomass regression curves	Forest Inventory and Analysis	Burril et al., 2021 Stanke et al. 2020
Protected forest areas	Vector map covering entire DRB	U.S. Geological Survey	USGS 2021
Riparian areas	Vector map covering entire DRB	U.S. Geological Survey	USGS 2019

To set the FVS input parameters for the three even-age regeneration forest management practices (clearcut, seed tree, and shelterwood), we identified how many legacy trees per acre would need to be left as reserves for each FVS run such that the percentage of merchantable volume removed would be as close as possible to the percentage of removed merchantable biomass in the DeLyser et al. (2022) paper's assumptions for clearcut, seed tree, and shelterwood treatments—DeLyser et al. (2022) modeled 90% removal for clearcut, 70% removal for seed tree, and 50% removal for shelterwood. We used these merchantable volume percentages to estimate the number of remaining trees in each scenario.

Increasing Carbon Removals from Farmland

We examined carbon and nitrous oxide emissions from DRB farmland under a range of conventional and regenerative practices using the Natural Resource Conservation Service's COMET-Farm model (NRCS, 2023). COMET-Farm is a detailed-processed based model that simulates flows of carbon and nitrogen in agricultural systems based on parameters for crop management practices, local weather conditions, and local soil properties.

We used statistics from the 2017 U.S. Census of Agriculture (NASS, 2019), the USDA Cropland Data Layer (NASS, 2023), and the Penn State Agronomy Guide (Duiker, 2022) to define crop management practices for conventional forage crop, cash grain, and perennial hay production rotations in the DRB. We used data from an analysis of crop rotation patterns in Pennsylvania to show that the most common crop rotations in the DRB include a 3yr corn-3yr alfalfa forage rotation (common on dairy farms), a corn grain -soybean cash grain rotation, and continuous non-alfalfa hay rotation (White, 2017). We then developed regenerative scenarios for each of these systems (Table 2) based on trends in sustainable farming practices and previous discussions with farmers in the region (Egan, 2021). We used 2017 crop yields from the U.S. Census of Agriculture for five counties in the DRB and estimated planting and harvest dates from NASS Planting Progress Reports (NASS 2019). We estimated nitrogen fertilizer application rates using formulas and tables presented in the Penn State Agronomy Guide (Duiker, 2021), taking into account credits for legume crops and cover crops and previous manure applications.

Local soil properties including clay content, depth, and water holding capacity can strongly influence carbon dynamics on any given site. The COMET model allows users to simulate cropping practices on specific farm fields selected using aerial imagery, with inherent soil properties for this field parameterized using spatially explicit data from the NRCS Soil Survey. To ensure that our COMET models captured a range of background soil conditions, we ran our conventional and regenerative cropping scenarios across multiple soil series.

To develop a representative sample of soil series in the DRB, we first cross-tabulated all pixels (30m x 30m) in the NLCD in the watershed classified as either pasture/hay or cropland against pixels in the gSSURGO soils database. We found that five soil series accounted for 15.5% of the area in the cropland class and 10.0% of the area in the pasture/hay land cover class (Table 6). We next randomly selected 10 points with the pasture/hay or cropland land use classes for each of these five abundant soil types. We located each point within the COMET field viewer, and mapped field boundaries for the closest farm field visible in the aerial imagery. We then parameterized COMET using both conventional and regenerative management practices.

We conducted a 2-way Analysis of Variance for both soil organic carbon and nitrous oxide rates for each cropping system separately, with soil series and cropping system (conventional or regenerative). We found significant differences between cropping systems, but not between soil series or the interaction of series and system. We therefore used a cross-soil series average value to scale up removals across the DRB for the location-based inventory.

Table 6. Common agricultural soil series in the Delaware River Basin selected for cropping system modeling using COMET-Farm. Example county lists the county where each soil type is most abundant.

Soil Series	Cropland Area (ha)	% of DRB Cropland Area	Pasture/Hay Area (ha)	% of DRB Pasture/Hay	Example County
Berks-Weikert complex	34,426	9.7	15,807	5.9	Berks, PA
Washington silt loam	12,613	3.6	3,469	1.3	Northampton, PA
Downer loamy sand	8,013	2.3	192	0.1	Kent, DE
Wellsboro channery loam	42	0	9,356	0	Wayne, PA
Willowemoc silt loam	37	0.0	7,480	2.8	Wayne, PA

We scaled to the watershed using statistics from the U.S. Census of Agriculture and the NLCD to estimate the land area over which each system could be applied. We assumed that the forage rotation would be practiced over twice the area planted to corn-silage, as reported in the Census of Agriculture (since this rotation is 3 years corn silage followed by 3 years alfalfa). We assumed that the grain rotation would be practiced over the total area classed as Cropland in the NLCD, minus the area allocated to the forage rotation. We assumed that perennial rotation could be practiced on all land classified as pasture/hay by the NLCD.

Land Use Alternatives

We compared land use alternatives using average per acre emission or removal values taken from other sections of this report or from estimates in the published literature. Table 7 summarizes our sources and assumptions for each of the land use alternatives presented in Figure 12.

Table 7. Greenhouse gas emission and removal factors and data sources for land use transitions in the Delaware River Basin.

Land Use Transition	Emissions or Removals ($t\ CO_2e/ha/yr$)	Method and Sources
Forest to Development	27.6	Assumed 74.0 t C/ha lost from Forests, caluclated using the ICLEI LEARN tool for the DRB, amortized for over a 20 year period. Assume additional emissions from new households are 15.6 mt CO2e/ha/yr, taken from McGill et al. 2022.
Cropland to Development	15.6	From McGill et al. 2022.
Forest to Pasture	5.01	Assumed 74.0 t C/ha lost from Forests, caluclated using the ICLEI LEARN tool for the DRB, amortized for over a 20 year period. Assumed carbon removals from pasture of 3.33 mt CO2e, calculated using the COMET model parameterized for perennial hay, as described in the "Increasing Carbon from Farmland" section.
Pasture as Pasture	-3.26	Assumed carbon removals from pasture of 3.33 mt CO2e, calculated using the COMET model parameterized for perennial hay, as described in the "Increasing Carbon from Farmland" section.
Forest as Forest	-6.42	Calculated using the ICLEI LEARN tool.
Pasture to Forest	-7.99	Calculated using the ICLEI LEARN tool.
Pasture to Solar	-172	Assume solar power production of 4.4 A/GWH/yr, value taken from NREL 2019, value for "Small Fixed PVs". Assumed solar electricity avoids electricity generated for the RFCE grid at 307 kg/mwh, from US EPA 2021a.

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