The Plantation Carbon Complex:

Slavery and the Origins of Climate Change in the Early Modern British Atlantic

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Appendix I: Methods and Sources

Methods: Land Use Emissions

This article uses the "bookkeeping" method to estimate agricultural land use and land cover change emissions for both individual plantations and farms, as well as agricultural exports.[1] The emissions models were designed with the help of Richard Houghton, a leading land use carbon emissions modeler and senior scientist emeritus at the Woodwell Climate Research Center, and in accordance with the principles laid out in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 4: Agriculture, Forestry and Other Land Use*.[2] Independent data scientist Deep Shah also helped build and calculate each of the land use models. To calculate agricultural land use and land cover change emissions using the bookkeeping method, three essential pieces of information are needed: the amount of carbon stored in different forest and soil types, known as "emissions factors"; the land category a forested area is being converted into—in this case, cropland or grassland, the latter of which includes both pasture and meadow; and the crop or field rotation pattern.

[1] Climate scientists generally use *land use* to refer to how a specific type of land—pasture, cropland, forest, and so on—is managed. *Land cover change* refers to the conversion of one type of land, such as forest, to another, such as cropland. In our model, the annual emissions from soil disturbance and methane emissions capture the "land use" aspect, while the emissions from the conversion of forests to cropland or pasture, and from cropland to pasture or fallow land, capture the "land cover change" dynamic.

[2] *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 4: Agriculture, Forestry and Other Land Use*, Intergovernmental Panel on Climate Change (IPCC), https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html.

For the emissions factors, all the models use the Tier 1 default values found in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 4: Agriculture, Forestry, and Other Land Use*.[3] When data was not updated in the 2019 refinement report, emissions factors from the previous *2006 IPCC Guidelines* report were used. If emissions factors were missing from both these reports, the emissions factors used by the U.S.D.A. Forest Service's Forest Inventory and Analysis (FIA) program were used.[4] (The specific emissions factors applied in each model, and the sources for them, can be found in Table A.I.1.) The models account for five major sources of carbon emissions, referred to as "pools" in the scientific literature, when forests are cleared and converted to another type of land use. For the rice estimates, a sixth pool was added—annual methane emissions.

The models assume that all the carbon stored in four of the five forest pools—above-ground biomass, below-ground biomass, dead wood biomass, and litter biomass—is released into the atmosphere upon the forest's transition into cropland or grassland. By contrast, the fifth pool for soil emissions (and, for rice, methane emissions) is applied annually, each year that cropland is actively being tilled. To calculate the annual emissions from tilled soil, it was assumed that 25 percent of the carbon stored in the soil was lost over a six-year period in all forms of tillage and this emission factor was applied annually to all active crop fields. Similarly, the carbon equivalent of the methane emission factor was applied annually to all active rice fields. The models also account for carbon drawdown or so-called negative emissions—carbon pulled out of the atmosphere—when one type of land transitions to another. For example, each time forest is

[3] *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 4: Agriculture, Forestry, and Other Land Use*, IPCC, https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html.

[4] Default values used by the U.S. Forest Service's FIA Program are found in Christopher Woodall, James Smith, and Michael Nichols, "Data Sources and Estimation/Modeling Procedures for National Forest System Carbon Stocks and Stock Change Estimates Derived from the US National Greenhouse Gas Inventory," May 22, 2013, U.S. Forest Service Research and Development, Northern Research Station, Table A-2 (pp. A-14 to A-16).

cleared for cropland, the amount of carbon stored in croplands was subtracted from the amount of carbon released into the atmosphere from the cleared forest. Similarly, the amount of carbon stored in grassland (either pasture or meadow) was subtracted from the amount of carbon emitted when croplands transition to pasture, were fallowed, or were completely abandoned.[5]

The models also account for certain unique features only relevant to specific crops and regions. As mentioned, methane emissions were included only in the rice plantation and rice export models, since rice fields, unlike other crops studied here, release a significant amount of methane annually while under cultivation. For New England and Pennsylvania farms, the models account for the fact that each year roughly one acre of forest was cut down for fuelwood to heat colonists' homes.[6] This annual acre of fuelwood clearance was not applied in the Chesapeake plantation models, even though Chesapeake planters also heated cabins with fuelwood in the winter. It was assumed that Chesapeake planters would have repurposed the wood from the forests they cleared and turned into tobacco fields, which provided far more than one acre's worth of wood each year, rather than clear virgin forests exclusively for heating-related needs. For the individual sugar plantation model, it was assumed that all the forested acreage remaining that was not cleared for sugar fields, provision grounds, the planter's estate, and the sugar works would have eventually been used for the fuelwood needed to boil cane juice into sugar. For the fuelwood needs in the sugar export emissions model, the model applies Jason W. Moore's ratio of 50 tons of fuelwood required to produce 1 ton of sugar, and 50 tons of fuelwood in 1 acre of

[5] Accounting for the negative emissions from completely abandoned croplands was only relevant in the export models, since the individual plantation and farm models only capture one twenty-six-year period in which fallowed land was returned to use, and no land was permanently abandoned. For the export models, it was assumed that all completely abandoned croplands converted to grassland, rather than forest, because livestock would have used this land for grazing, or the increasing human population would have settled on it. In both cases, forests would not have been able to grow on the abandoned crop fields.

[6] One acre of fuelwood per year derived from William Cronon, *Changes in the Land: Indians, Colonists, and the Ecology of New England* (New York, 1983), 120.

Brazilian forest—so 1 acre of fuelwood for every 1 ton of sugar (this was the best option available, given the difficulty finding an estimate of tons of fuelwood per acre in Caribbean forests).[7]

To determine land use practices—from the amount of acreage in croplands, pastures, meadows, and dwellings to the crop and field rotation patterns—this article relied on secondary literature and, whenever possible, corroborated or refined this information with data from primary sources. (See Appendix II, Tables I–VIII, for a detailed breakdown of acreage, crop and field rotations, and sources for individual household and plantation models.) Whereas certain land use practices were simple to find and widely accepted by scholars, such as shifting long-fallow land use for average tobacco growers, others—such as acreage for pastures and meadows for livestock, in all regions—came with much more uncertainty.[8] For instance, descriptions of Pennsylvania livestock management practices suggest that, similar to tobacco planters, Pennsylvania farmers did not reserve much cleared land for livestock. Yet James T. Lemon, a leading scholar of colonial Pennsylvania farming practices, nevertheless estimates thirty-three acres in pasture and meadow, though still acknowledging that livestock acquired additional food by foraging in uncut forests.[9]

In addition, it is impossible to know whether those thirty-three acres in pastures and meadows were forested land cleared explicitly for pastures and meadows or a combination of

[7] Jason W. Moore, "Ecology and the Rise of Capitalism" (Ph.D. diss., University of California, Berkeley, 2007), 433, 437.

[8] See for example Carville Earle, *The Evolution of a Tidewater Settlement System: All Hallow's Parish, Maryland, 1650-1783* (Chicago, 1975), 24–30; Allan Kulikoff, *Tobacco and Slaves: The Development of Southern Cultures in the Chesapeake, 1680–1800* (Williamsburg, Va., and Chapel Hill, N.C., 1986), 47–48; Lorena S. Walsh, "Land Use, Settlement Patterns, and the Impact of European Agriculture, 1620–1820," in *Discovering the Chesapeake: The History of an Ecosystem*, ed. Philip D. Curtin, Grace S. Brush, and George W. Fisher (Baltimore, 2001), 220–48, esp. 222.

[9] James T. Lemon, *The Best Poor Man's Country: A Geographical Study of Early Southeastern Pennsylvania* (Baltimore, 1972), 152–53 (table 27), 167–69.

repurposed fallowed cropland and naturally occurring meadows, neither of which would have required additional deforestation. Despite these uncertainties, the Pennsylvania and New England household models assume that all pasture and meadowland began as forested land that was completely cleared for meadows and pastures, and therefore these individual household models might overestimate their emissions.[10] For all the tobacco plantation models, cleared acreage for pasture or meadows was not included, despite the similarities between livestock management in the Chesapeake and Pennsylvania. Pasture and meadow clearance was excluded for the tobacco plantation models due to the uncertainties around pasture and meadow acreage and to avoid assumptions that would bias the results in favor of enslaved-based emissions. The tobacco plantation emission figures therefore likely underestimate their actual emissions.

The export emission estimates (Figures II–III in the article) only account for the land cleared and soil disturbed for the specific export crop, not all the land cleared for an entire plantation or farm producing the crop. As the household land use data indicate, however, farmers and planters cleared considerably more land to feed themselves, their workforces, and in some cases their livestock than they cleared for the export crop itself; therefore, the export emission figures do not account for each crop's full export emissions.[11] (Additional acreage was excluded due to the difficulty determining the number, size, and share of the plantations and farms producing the exports.) The tobacco export model assumes that croplands were used for three cycles before being completely abandoned, with one cycle being three years in tobacco, followed by three years in grain, then a twenty-year fallow period. It also assumes that, for the entire

[10] Brian Donahue, email communication to authors, Nov. 23, 2022.

[11] It is also worth noting that the export emission figures for seventeenth-century tobacco, produced largely by indentured servants, might overestimate the amount of land clearance that occurred in the first few decades of colonization. Much of the land taken by early settlements in colonial Virginia had already been cleared by Indigenous Americans. See John Brooke, "Ecology," in *A Companion to Colonial America*, ed. Daniel Vickers (Malden, Mass., 2003), 44–75, esp. 59–63; Strother E. Roberts, *Colonial Ecology, Atlantic Economy: Transforming Nature in Early New England* (Philadelphia, 2019), 73.

colonial period, one-third of the fallowed land available for reuse after a twenty-year fallow was actually reused. (A similar one-third fallow reuse figure was applied for Chesapeake grain.) This captures the fact that most planters likely cleared as much virgin land as possible before returning to their rested fallow land, even if it could be reused in twenty years, since even long-fallowed land had less soil fertility than virgin forest. For fallowed land that was re-cleared after twenty years, the model assumes that the land stored half as much carbon per acre as the virgin forest it originally replaced.

Sources for Export Crop Data and Methods for Conversion to Cultivated Acres[12]

The raw data for the export amounts of tobacco and rice were derived from the colonial statistics chapter in the *Historical Statistics of the United States: Millennial Edition*, edited by Susan B. Carter et al.[13] To convert tons of tobacco exported into acreage needs, the ratio of 2.5 acres producing 1,000 pounds of tobacco was used for the entire colonial period, as well as the standard rotation pattern of three years of tobacco, followed by three years of corn, then twenty years fallow.[14] For rice, the model uses the average inland swamp irrigation yield of 800 pounds of rice per acre and assumes no crop or field rotation due to the fertile deep soils in the rice fields.[15]

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[12] For individual farm and plantation emissions, see Appendix II, Tables I–VIII.

[13] John J. McCusker, "Table Eg1054–1056: English Colonial Tobacco Imported into England: 1615–1701," "Table Eg1038–1045: Tobacco Imported into England, by Origin: 1697–1775," and "Table Eg1160–1165: Rice Exported from South Carolina and Georgia: 1698–1790," all in "Chapter Eg: Colonial Statistics," in *Historical Statistics of the United States: Millennial Edition*, ed. Susan Carter et al. (Cambridge, 2006).

[14] For 1,000 pounds of tobacco per year over the course of both the seventeenth and eighteenth centuries, see Lorena S. Walsh, *Motives of Honor, Pleasure, and Profit: Plantation Management in the Colonial Chesapeake, 1607–1763* (Williamsburg, Va., and Chapel Hill, N.C., 2010), 183 (table 11), 542 (table 30). For the average of two to three acres reserved for tobacco per laborer, see Earle, *Evolution of a Tidewater Settlement System*, 27; Kulikoff, *Tobacco and Slaves*, 47; Philip D. Morgan, *Slave Counterpoint: Black Culture in the Eighteenth-Century Chesapeake and Lowcountry* (Williamsburg, Va., and Chapel Hill, N.C., 1998), 42.

[15] For 800 pounds of rice per acre for inland swamp irrigation, see Joyce E. Chaplin, *An Anxious Pursuit: Agricultural Innovation and Modernity in the Lower South, 1730–1815* (Williamsburg, Va., and Chapel Hill, N.C., 1993)¸ 247. Though inland swamp irrigation produced lower rice yields per acre than tidal irrigation, inland swamp

For the sugar export data, a variety of secondary sources were consulted, and linear interpolation was used to impute the data for years in which export quantities were missing.[16] It was assumed that one acre of land produced 0.88 tons of sugar, based on the average sugar yields for all the British sugar islands from 1649 to 1822.[17] There is no available information on how many years cane fields were used consecutively before being fallowed, and thus an educated guess of twenty years was applied. This was because sugar planters did not quickly abandon their cane fields, as tobacco planters had, and instead intensively manured their cane fields to prolong fertility as long as possible. For sugar production fuelwood needs, the model applies Moore's ratio of 1 acre of fuelwood for every 1 ton of sugar, and assumes this ratio fully applied in the seventeenth century, then gradually tapered down to one quarter of that ratio by 1775—or 0.25 acres of fuelwood per one ton of sugar. This taper-down effect was included because sugar producers rapidly exhausted their islands' fuelwood within a generation (defined here as twenty-five years), then switched to sugar production methods that required much less fuelwood, such as using *bagasse* (used cane reeds) for fuel and adopting the "Jamaica train" boiling method, which required less fuelwood.[18]

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irrigation was the dominant practice for most of the colonial period. For the lack of rotation needs for rice, see Hayden R. Smith, "Reserving Water: Environmental and Technological Relationships with Colonial South Carolina Inland Rice Plantations," in *Rice: Global Networks and New Histories*, ed. Francesca Bray et al. (Cambridge, 2015), 189–211, esp. 193; Peter Coclanis, email communication to authors, Dec. 15, 2021.

[16] For sources of sugar exports, see Noel Deerr, *The History of Sugar* (London, 1949), 1: 158–82, 193–204; Ralph Davis, *The Rise of the Atlantic Economies* (Ithaca, N.Y., 1973), 257; Richard S. Dunn, *Sugar and Slaves: The Rise of the Planter Class in the English West Indies, 1624–1713* (New York, 1973), 203; John Richards, *The Unending Frontier: An Environmental History of the Early Modern World* (Berkeley, Calif., 2003), 439–57; Niels Steensgaard, "The Growth and Composition of the Long-Distance Trade of England and the Dutch Republic before 1750," in *The Rise of Merchant Empires: Long-Distance Trade in the Early Modern World, 1350–1750*, ed. James D. Tracy (Cambridge, 1990), 102–52, esp. 137–40.

[17] Stuart Schwartz, *Sugar Plantations in the Formation of Brazilian Society: Bahia, 1550–1835* (Cambridge, 1985), 114 (Table 5.4). This table provides information on the British islands, despite the book's focus on Brazilian plantations.

[18] J. H. Galloway, "Tradition and Innovation in the American Sugar Industry, c. 1500–1800: An Explanation," *Annals of the Association of American Geographers* 75, no. 3 (September 1985): 334–51 (quotation, 342); David Watts, *The West Indies: Patterns of Development, Culture and Environmental Change since 1492* (Cambridge, 1987), 398–99.

Northern grain export data were derived from James F. Shepherd and Gary M. Walton, *Shipping, Maritime Trade, and the Economic Development of Colonial North America.* For the northern grain export data—which includes wheat, bread, corn, and flour—annual export amounts were only available for 1768 through 1772.[19] Missing export data was imputed back to 1701 using a simple population-to-export ratio. To convert tons of bread and flour into bushels, it was assumed that one ton of bread or flour equaled 51.4 bushels of wheat, and one acre yielded 10 bushels of wheat.[20] For corn, it was assumed that one acre yielded 15 bushels of corn. It was assumed that all preprocessed grains (corn and wheat) could be grown on the same field for six years, and the fields were then fallowed for six years before being reused.[21] The model assumes that reused northern grain fields could only be used for three six-year cycles before being completely abandoned due to lost soil fertility.

Chesapeake grain export emissions are derived from Virginia grain exports from 1701 to 1773, compiled by Peter V. Bergstrom from customs data.[22] Unlike northern grain export data, Bergstrom's grain data only includes exports of corn and wheat, not bread or flour. Because the data is only for Virginia, not Maryland, grain export data for Maryland was imputed using colonial Maryland's population size and applying the same grain-to-population ratio for Virginia to Maryland. The model applies the same assumptions for northern grains regarding yields of wheat and corn per acre: 10 bushels of wheat per acre and 15 bushels of corn per acre.[23] The

[19] James F. Shepherd and Gary M. Walton, *Shipping, Maritime Trade, and the Economic Development of Colonial North America* (1972; repr., Cambridge, 2010), 211–27 (appendix 4, tables 2–6), and based on customs data found in CUST 16/1, National Archives of the United Kingdom (NAUK).

[20] For tons of bread and flour to bushels of wheat ratio, see David Klingaman, "The Significance of Grain in the Development of the Tobacco Colonies," *Journal of Economic History* 29, no. 2 (June 1969), 268–78, esp. 272; for bushels of wheat per acre, see Lemon, *Best Poor Man's Country*, 152 (table 27).

[21] Lemon, *Best Poor Man's Country*, 152 (table 27), 169–70.

[22] Peter V. Bergstrom, "Markets and Merchants: Economic Diversification in Colonial Virginia, 1700–1775" (Ph.D. diss., University of New Hampshire, 1980), 136 (table 5.2: "Virginia Exports, 1701–1773").

[23] Wheat yields in the Chesapeake ranged widely, from 5 to 40 bushels per acre. But given that wheat was grown on worn-out soils, we chose the more conservative figure of 10 bushels per acre, similar to the figure Lemon

main difference between the Chesapeake grain and northern grain export models is in the field rotation patterns. It was assumed that Chesapeake grains followed the same shifting long-fallow pattern as diversifying tobacco plantations, with corn and wheat grown on abandoned tobacco land for three years before that land was fallowed for twenty years. It was also assumed that Chesapeake grain fields were used for only two cycles before being completely abandoned, since, unlike northern grains, Chesapeake grains were grown on used tobacco fields, which had less fertility and could not withstand as many cycles as northern grain fields.

For British coal emissions, carbon emissions data for 1751 to 1800 comes from the national data set for fossil fuel and cement emissions for 1751–2020 compiled and managed by Matthew Hefner and Greg Marland.[24] For coal emissions data for 1600 to 1750, the ratio of coal-to-carbon emissions for 1751–1800, or 2.15 metric tons of coal per one metric ton of carbon, was applied to the known quantities of British coal production, excluding exported coal, from 1600 to 1750.[25]

uses for Pennsylvania. For wheat yields in the Chesapeake, see Harold B. Gill Jr., "Wheat Culture in Colonial Virginia," *Agricultural History* 52, no. 3 (July 1978): 380–93, esp. 393. See also Lemon, *Best Poor Man's Country*, 152 (table 27). For corn yields, see David O. Percy, *Corn: The Production of a Subsistence Crop on the Colonial Potomac*, National Colonial Farm Research Report, no. 2 (Accokeek, Md., 1977), 19.

[24] M[atthew] Hefner and G[reg] Marland, "Global, Regional, and National Fossil-Fuel CO2 Emissions: 1751–2020 CDIAC-FF," Research Institute for Environment, Energy, and Economics, Appalachian State University (2023), last accessed Dec. 12, 2023, https://energy.appstate.edu/cdiac-appstate/data-products.

[25] Sources for British coal production prior to 1751 are J. U. Nef, *The Rise of the British Coal Industry* (London, 1932), 1: 20; Michael W. Flinn, *The History of the British Coal Industry*, vol. 2, *1700–1830: The Industrial Revolution* (Oxford, 1984), 26; B. R. Mitchell, *International Historical Statistics: Europe, 1750–1993*, 4th ed. (New York, 1998), 426, 428, 431; John Hatcher, *The History of the British Coal Industry*, vol. 1, *Before 1700: Towards the Age of Coal* (Oxford, 1993), 68.