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Climate-focused Life Cycle Assessments of Biochar Production by an ARTi Pyrolysis Reactor and an Air Burners CharBoss® Air Curtain Incinerator

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Climate-focused Life Cycle Assessments of Biochar Production by an ARTi Pyrolysis Reactor and an Air Burners CharBoss® Air Curtain Incinerator

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24 March 2025

This report presents a limited, dynamic, consequential life cycle assessment (LCA) to compare the climate impacts of two biochar production methods using wood as a feedstock. The two methods are a pyrolysis reactor supplied by ARTi (Des Moines, IA, https://www.arti.com/) and a T26 CharBoss® air curtain incinerator supplied by Air Burners, Inc. (Palm City, FL, https://airburners.com/).

The underlying LCA methodology is described in a chapter by Singh et al. (2024) and implemented in the form of a workbook freely available as online Supplementary Material for the chapter. For the convenience of the reader, a pre-print version of the relevant portions of Singh et al. (2024) is attached as Appendix A to this report. Specific assumptions and calculations to obtain the input parameters used in this LCA for each production method are described in the Methodology section below. This implementation of the LCA considers emissions associated with biomass loading, comminution and conversion, biochar decay in soil, and the production and use of bioenergy generated during the conversion process.

The LCA is "limited" in that upstream emissions associated with biomass production, harvest, transportation, and land-use change, as well as embodied emissions in equipment and facilities are not considered. Similarly, downstream emissions from biochar transport and incorporation into soil (i.e., tillage), and the impact of biochar soil amendments on soil greenhouse gas (GHG) emissions (other than CO_2 from biochar decay in soil), soil organic carbon stocks, crop response, and surface albedo are not considered.

As the intent is to compare different biochar production methods in a simple unbiased manner, the primary alternative biomass pathway for the LCA is *immaculate combustion*, which is the hypothetical instantaneous and complete conversion of carbon in the biomass to CO_2 at time zero without generation of any other greenhouse gases or aerosols (GHGAs) or any useful bioenergy. Use of this pathway provides relative values for the production methods and, when the embodied emissions are similar and the same feedstock is used, these relative values are reasonable approximations for those attained with a full LCA.

Methodology

The LCA requires 8 input parameters if no bioenergy is generated and 14 when bioenergy is generated and used (Table 1). Singh et al. (2024) describe the general aspects of these parameters. Here, I describe how the specific values for the parameters were obtained for each biochar production method.

Common Parameters. Values common to all production methods include mean annual soil temperature (15.0°C), concentrations of biomass C (0.503 mass fraction, dry basis) and H_2O (0.189 mass fraction, wet basis), biomass lower heating value (LHV, 18.53 GJ / t dry matter), biochar higher heating value (HHV, 31.2 GJ / t dry matter), and C intensity of the primary energy supply (45.91 kg CO_2 / GJ). Mean annual soil temperature is taken as the mean annual air temperature for Sonoma, CA (1981-2010 normals, Lat. 38.2574°, Long. -122.434°, https://www.usclimatedata.com/climate/sonoma/california/united-states/usca1076#google_vignette) near where the biochar would likely be used as a soil amendment. Biomass properties (C, H_2O, and LHV) are the global averages for wood from Woolf et al. (2010) assuming 29% hardwood and 71% softwood. Biochar HHV is the value for waste wood biochar given by Woolf et al. (2010). The C intensity of the primary energy supply is the 2021 average for California (USEIA, 2023, Table 6).

ARTi Pyrolysis Reactor. A dataset collected on a small test reactor (the ARTi Activator Kiln) was used pending measurement of a full dataset for the production-scale reactor purchased for this project and expected to be installed at the Napa Recycling and Waste Services facility located in American Canyon, CA in the first quarter of 2025. The properties of the biochar (i.e., atomic H/C_{org}, C content) are taken from the results of an analysis by Control Laboratories (Watsonville, CA) of a sample received from ARTi on 23 July 2021 (Lab ID #1070599-01, ARTi Sample ID of "Woodchips strip BC 500 C 5 Hz"). Biogenic emissions of CH_4, N_2O, and Black C during biochar production were estimated from measurements of CH_4, NOx, and PM2.5 conducted during a test on the ARTi Activator Kiln performed in Prairie City, Iowa on July 29, 2021 (Comprehensive Emission Services, 2021). The N_2O fraction of NOx emissions and the Black C fraction of PM2.5 emissions (e.g., Snider et al. 2016) were both estimated at 10%. Based on process notes received from ARTi for the emission-testing run (Carlos J. Rosero, personal communication, 18 August 2021) and the C content of the biochar from the Control Laboratories analysis, the carbon efficiency of production (i.e., C_{eff}, the fraction of biomass C that was incorporated into the biochar) was estimated at 34.5%. This analysis assumes that the reactor, feedstock, and operating conditions were the same for the biochar analyzed earlier as for the emissions test.

Fossil CO_2e emissions by the ARTi unit (30.26 kg CO2e / t dBM) are estimated as the sum of emissions for wood chip production and for an excavator to collect and load biomass into the chipper. The type of chipper was unknown, so a diesel-fueled chipper was chosen as the most conservative (i.e., having the highest GHGA emissions) assumption. The diesel fuel consumption per tonne of dry biomass (2.50 L / t dBM) for chipping was based on data of Weyrens et al. (2022). Diesel fuel consumption for loading (1.13 L / t dBM) is based on Johannesson et al. (2024, Table 2, p. 17). The total diesel fuel consumption (3.63 L / t dBM) was multiplied by the diesel fuel emission factor (8.33 kg CO_2e / L diesel fuel), which is the sum product of USEPA emission data for CO_2, CH_4, N_2O and Black-C (USEPA, 2023; USEPA, 2024; Kholod, 2016; CEQA 2006) and their respective mean 100-year GWPs (Singh et al. 2024). For the scenario in which bioenergy is generated, the relative energy recovery efficiency was assumed to be 0.75 as suggested by Woolf et al. (2010) for generic pyrolysis-based energy production systems. For the scenario without bioenergy generation, the relative energy recovery efficiency was set to zero.

T26 CharBoss® Air Curtain Incinerator. Chemical properties of the biochar and C_{eff} (23.4%) are obtained from Johannesson et al. (2024, Table 11, p. 34). Biogenic emission factors are calculated from air quality testing data (Montrose Air Quality Services, 2023, p. 30-34) collected for a BurnBoss® T24 air curtain incinerator (Air Burners, 2023) located in Hillsboro, OR. This incinerator is nearly identical to the CharBoss® T26 machine (e.g., it has the same size firebox and air-curtain capacity) but lacks the charcoal collection apparatus on the bottom of the firebox (Air Burners, 2023, 2024). The N_2O and Black-C emissions were estimated as 10% of the measured NOx and filterable PM emissions, respectively.

As with the ARTi unit, the mean 100-year fossil CO_2e emissions by the CharBoss® unit (79.05 kg CO2e / t dBM) are estimated from nominal diesel fuel consumption for the engine that powers the air-curtain and charcoal-collection apparatus (7.89 L / t dBM, Air Burners, 2024) and for an excavator to collect and load biomass into the firebox (1.13 L / t dBM, Johannesson et al., 2024, Table 2, p. 17). The total diesel fuel consumption (9.02 L / t dBM) was multiplied by the diesel fuel emission factor (8.33 kg CO_2e / L diesel fuel) to obtain the 100-year mean GWP. Because no useful energy is recovered by the CharBoss® unit the relative energy recovery efficiency is set to zero.

Table 1. Input parameters used to calculate component Climate Impacts of Biochar Production ($CI_{XXXX}100$) for the ARTi pyrolysis reactor, ARTi pyrolysis reactor w/ bioenergy, and the CharBoss® air curtain incinerator.

Input Variable	Units	Biochar Production System		
		ARTi Pyrolysis Reactor	ARTi Pyrolysis Reactor w/Bioenergy	CharBoss® Air Curtain Incinerator
Carbon Efficiency and Soil Permanence ($CI_{CESP}100$)				
Mean Annual Soil Temperature	°C	15.0	15.0	15.0
Biochar H/C_{org} (atomic ratio)	--	0.500	0.500	0.181
Carbon Efficiency of Production (C_{eff})	--	0.345	0.345	0.234
Production Emissions ($CI_{PEMI}100$)				
Biomass C Content	mass fraction, dry	0.503	0.503	0.503
Fossil CO_2e Emissions	g CO_2e / kg dry biomass	30.26	30.26	79.05
Biogenic CH_4 Emissions	g CH_4 / kg dry biomass	0.0745	0.0745	0.4082
Biogenic N_2O Emissions	g N_2O / kg dry biomass	0.1850	0.1850	0.1206
Biogenic Black Carbon Emissions	g Black Carbon / kg dry biomass	0.1247	0.1247	0.2106
Production Bioenergy ($CI_{ENER}100$)				
Biomass H_2O Content	mass fraction, wet basis	0.189	0.189	0.189
Biomass Lower Heating Value (LHV)	GJ / tonne dry matter	18.53	18.53	18.53
Biochar C Content (BCC)	mass fraction, dry	0.702	0.702	0.6767
Biochar Higher Heating Value (HHV)	GJ / tonne dry matter	31.2	31.2	31.2
Relative Energy Recovery Efficiency	fraction of theoretical maximum	0	0.75	0
C Intensity of Primary Energy Supply	kg CO_2 / GJ	45.91	45.91	45.91

Results

This limited LCA provides results in terms of the Biochar Production Climate Impact (Singh et al. 2024), which has units of tonnes CO2e / tonne *biomass* C (t CO2e / t BMC). The choice of denominator emphasizes the importance of maximizing the efficient conversion of biomass C, a limited global resource that ultimately constrains the amount of biochar that can be made. Values are calculated on an annual basis and then averaged for the given period of interest which, for this LCA, is 100 years. The Biochar Production Climate Impact is represented by $CI_{PROD}100$, where the subscript refers to the type of biochar climate impact and the numerals at the end to the period of interest (years).

To aid interpretation of the results, values for three focused biochar climate impacts (which sum to yield $CI_{PROD}100$) are also given. These are:

- $CI_{CESP}100$, which considers *carbon efficiency* of biomass conversion and biochar *soil permanence*
- $CI_{PEMI}100$, which addresses *production emissions* other than biogenic CO_2, and
- $CI_{ENER}100$, which accounts for net *bioenergy* supplied by the process.

Screen shots of the Main User Portal in the workbook (Singh et al. 2024) used to calculate the LCA results for each biochar production system are provided in Appendix B. These show the input values (column D, green cells in rows 20-40), the resulting Climate Impact Classification (columns A and B, rows

3-8), and the Average 100-year Climate Impacts relative to the Immaculate Combustion alternative biomass pathway (columns A, C, D, and E, rows 3-8).

The Average 100-year Climate Impacts for the three systems assessed are listed in Table 2. These values assume that immaculate combustion is the alternative biomass pathway. Thus, positive values in the table indicate that the alternative biomass pathway contributes fewer CO_2 equivalents to climate warming than the biochar production system for a given scenario. Negative values indicate that the biochar production system contributes fewer CO_2 equivalents than the alternative pathway.

Table 2. Average 100-year Climate Impacts (t CO_2e / t biomass C) for biochar production by the ARTi pyrolysis reactor, ARTi pyrolysis reactor w/ bioenergy, and the CharBoss® air curtain incinerator relative to the Immaculate Combustion alternative biomass pathway, a hypothetical construct that assumes complete, instantaneous conversion of biomass to CO_2 at time zero with no emissions of other GHGAs or generation of useful bioenergy (Singh et al. 2024).

Average 100-year Climate Impacts[a]	**Biochar Production System**		
	ARTi Pyrolysis Reactor	ARTi Pyrolysis Reactor w/Bioenergy	CharBoss® Air Curtain Incinerator
Carbon Efficiency and Soil Permanence ($CI_{CESP}100$)	-0.58	-0.58	-0.43
Production Emissions ($CI_{PEMI}100$)	0.89	0.89	1.45
Production Bioenergy ($CI_{ENER}100$)	0.00	-0.36	0.00
Total Biochar Production Climate Impact ($CI_{PROD}100$)	**0.31**	**-0.05**	**1.02**

[a]Relative to the *Immaculate Combustion* alternative biomass pathway, a hypothetical construct that assumes complete, instantaneous conversion of biomass to CO_2 at time zero with no emissions of other GHGAs or generation of useful bioenergy (Singh et al. 2024)

Of the three biochar production systems assessed, the ARTi reactor with generation of useful bioenergy has about the same climate impact as the immaculate combustion biomass alternative (Table 2). The CharBoss® air curtain incinerator contributes about 1 t CO2e / t biomass C more than the biomass alternative. All three biochar production systems have negative climate impacts based on C_{eff} and biochar quality ($CI_{CESP}100$). They differ significantly with respect to production emissions ($CI_{PEMI}100$), where the CharBoss® has about 60% higher climate impact from emissions than the ARTi reactor. An additional climate benefit of -0.36 t CO2e / t biomass C is generated when the ARTi reactor is used to generate useful bioenergy ($CI_{ENER}100$).

The outcome of a consequential LCA is strongly influenced by the alternative pathway selected for comparison with the targeted pathway. To provide some perspective, I ranked estimates of the absolute average 100-year climate impacts for a full range of possible (and hypothetical) biochar production and biomass conversion pathways that use wood as a feedstock (Table 3, Figure 1). According to this ranking, slash pile burns and moderate wildfires have the highest warming impacts on climate, followed by landfilling. Pathways having the least warming impact on climate include the hypothetical immaculate biochar production with bioenergy, and an automated gasifier with full emission controls producing biochar and bioenergy. Flame-cap kilns, the CharBoss® air curtain incinerator, the ARTi pyrolysis reactor with and without bioenergy, chipping and spreading (assuming no risk of subsequent wildfire), and immaculate combustion represent median values in this ranking.

Table 3. Comparison of the absolute Average 100-year Climate Impacts for biochar production by the CharBoss® air curtain incinerator, ARTi pyrolysis reactor, and ARTi pyrolysis reactor w/ bioenergy with Climate Impacts for alternative biochar-production and biomass-conversion approaches

Woody Biomass Fate	**Absolute $CI_{PROD}100^a$**
	$t\ CO_2e_{100}$ /t biomass C
Slash Pile Burn	12.6
Moderate Wildfire	12.4
Landfill	7.78
Flame-Cap Kiln	3.21
CharBoss® Air Curtain Incinerator	**2.92**
ARTi Pyrolysis Reactor	**2.22**
Chip & Spread	1.95
Immaculate Combustion [b]	*1.91*
ARTi Pyrolysis Reactor w/bioenergy	**1.86**
Gasifier w/bioenergy & emission controls	0.91
Immaculate Biochar w/maximum bioenergy [c]	*0.58*

[a] Absolute Average 100-year Climate Impact of Biochar Production without reference to alternative biomass pathways

[b] Hypothetical construct that assumes complete, instantaneous conversion of biomass to CO_2 at time zero with no emissions of other GHGAs or generation of useful bioenergy

[c] Hypothetical construct representing the maximum potential biochar climate benefit that assumes complete, instantaneous conversion of biomass to biochar and CO_2 at time zero (45% C effic., 90% biochar C, 0.10 H/Corg), no emissions of other GHGAs, and generation and use of 100% of the potential bioenergy

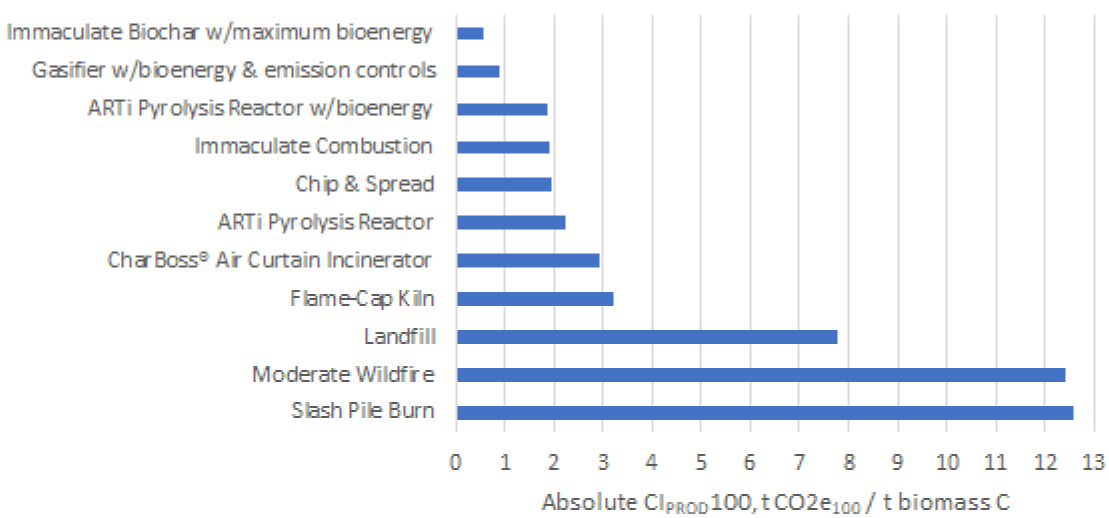

Figure 1. Range of absolute Average 100-year Climate Impacts for selected biochar production and biomass conversion approaches.

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Appendix A: Pre-proof excerpt from Singh et al. (2024).

This is a peer-reviewed "pre-proof" excerpt of the Introduction and Climate-Impact Value and Classification sections from:

Singh, B, JE Amonette, M Camps-Arbestain, & RS Kookana. 2024. A Biochar Classification System and Associated Test Methods. Chpt. 9 In (J. Lehmann and S. Joseph, eds*) Biochar for Environmental Management, 3rd ed*. Routledge.

A Biochar Classification System and Associated Test Methods

Balwant Singh

James E. Amonette

Marta Camps-Arbestain

Rai S. Kookana

Abstract

This chapter proposes classification schemes for biochar for different applications. The classification schemes for climate impact value, fertilizer value, and liming values are well developed as the required data are available for a range of biochars. The classification schemes for particle size and binding pesticides and organic contaminants are broad and can be refined as more relevant data become available. The section on biochar's use as a substrate in potting media and soilless agriculture is provisional and needs substantial data and research before a classification scheme can be devised. Analytical methods needed for the proposed classification scheme are also provided in the chapter.

Introduction

In this chapter, a biochar classification system is presented as it relates to its use as a soil amendment. It builds on a previous classification system (Camps-Arbestain et al, 2015) and two fundamental biochar standards/guidelines: "Standardized product definition and product testing guidelines for biochar that is used in soil" (IBI, 2015) (aka IBI Biochar Standards) and "Guidelines for sustainable production of biochar: European Biochar Certificate" (EBC, 2012-2022) (aka EBC Guidelines). The scope of this classification system is constrained to materials with properties that satisfy the criteria for biochar as defined by either the IBI Biochar Standards or the EBC Standards (Annex I). Both the IBI Standards and the EBC

Guidelines are product-quality certifications, but do not constitute a certificate for issuance of carbon credits. The classification system will enable stakeholders and commercial entities to (i) assess the climate-impact (CI) value based on biochar properties, soil temperature, and production factors including carbon efficiency, emissions, and bioenergy; (ii) identify the most suitable biochar to fulfil the requirements for a particular soil and/or land-use; and (iii) distinguish the application of biochar for specific niches (e.g., soilless agriculture). This classification system is based on the best current knowledge and will need to be improved as new data and knowledge become available in the scientific literature. The use of biochar in materials (e.g., cement, concrete, asphalt) is excluded from the scope of this chapter.

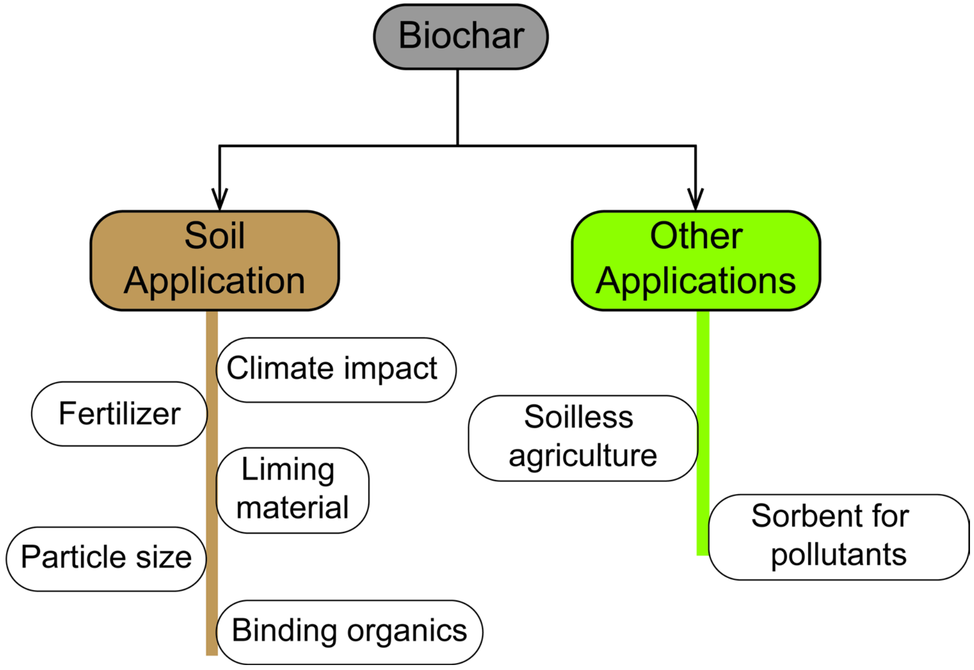
Biochar classification system

The main thrust of this classification system is the direct or indirect effects that biochar provides from its application to soil or other applications of biochar (e.g., environmental) as depicted in Figure 9.1. The potential effects of biochar from soil and other applications are classified into different categories (Figure 9.1) and provided classes for: (i) climate impact; (ii) fertilizer value; (iii) liming value; (iv) particle-size; and (v) binding organic agrochemicals in the following sections.

Figure 9.1 *A classification system of biochar based on its effects from soil and other applications.*

Climate-impact value and classification

The impact of a biochar on climate depends on many factors (Woolf et al, 2010; Cowie et al, 2015; Verheijen et al, 2015; Amonette et al, 2021; Chapter 30). Historically, the primary focus has been on the C-storage properties of biochar with the result that persistence of biochar C in soil is moderately well understood (Lehmann et al, 2015; Chapter 11) and it has been used as one of the criteria for classification of biochars (Camps-Arbestain et al, 2015). A full representation of the climate impact, however, requires a life cycle assessment (LCA) approach that starts with the biomass C and compares the release of greenhouse gases and aerosols (GHGAs) from the biomass during biochar production and its subsequent application to soil, with the GHGAs released when the same biomass is used in other pathways. A full LCA of each biochar and biomass combination is impractical for most



Biochar
Soil Application
Other Applications
Climate impact
Fertilizer
Liming material
Particle size
Binding organics
Soilless agriculture
Sorbent for pollutants

Fig. 9.1

classification purposes. However, a limited assessment using readily available inputs, can capture the essential elements related to production and soil deployment of biochar and thereby provide a more realistic estimate of its climate impact (CI) than reliance on C-storage properties alone.

Here, an LCA-based biochar classification system (Figure 9.2) is presented that considers C efficiency of biochar production and soil permanence (CESP), biomass harvest, pre-processing and conversion emissions (PEMI), and production of bioenergy to offset fossil energy (ENER) in the biochar pathway. To focus on the relative differences among biochars, all aspects of biochar production are compared against a single, hypothetical, and easily quantifiable biomass reference pathway that is termed here "immaculate conversion to CO_2", for which no biomass C permanence exists, no other GHGA emissions are generated, and no bioenergy is produced. To keep the calculations simple, neither upstream emissions from biomass production (including land-use change) nor embodied emissions associated with manufacture of equipment and facilities are considered. More, any biomass supply chain will have to avoid the following (Woolf et al, 2010): clearance of natural undeveloped lands; conversion of land from production of food crops to biomass; biomass extraction rates that engender loss of soil function; and use of contaminated waste biomass. Downstream emissions from biochar transport and tillage, and from the impact of biochar amendments on soil GHG emissions, organic C stocks, productivity, and surface albedo are excluded. These downstream parameters either contribute little to the overall climate impact (Woolf et al, 2010), are highly location-dependent, or are not sufficiently well understood to include in the limited LCA analysis.

Figure 9.2 *Overview of processes and variables included in and excluded from the simple life cycle assessment (LCA)-based classification of biochar.*

As the primary CI criterion for classification, the average mass of GHGAs released into the atmosphere are calculated over a 100-year period per unit mass of biomass C that was converted at the start of Year 1. Separate 100-year CI values are computed for each portion of the biochar pathway (i.e., $CI_{CESP}100$, $CI_{PEMI}100$, and $CI_{ENER}100$) and then added to obtain the 100-year Biochar Production Climate Impact ($CI_{PROD}100$). All CI values have units of tons of

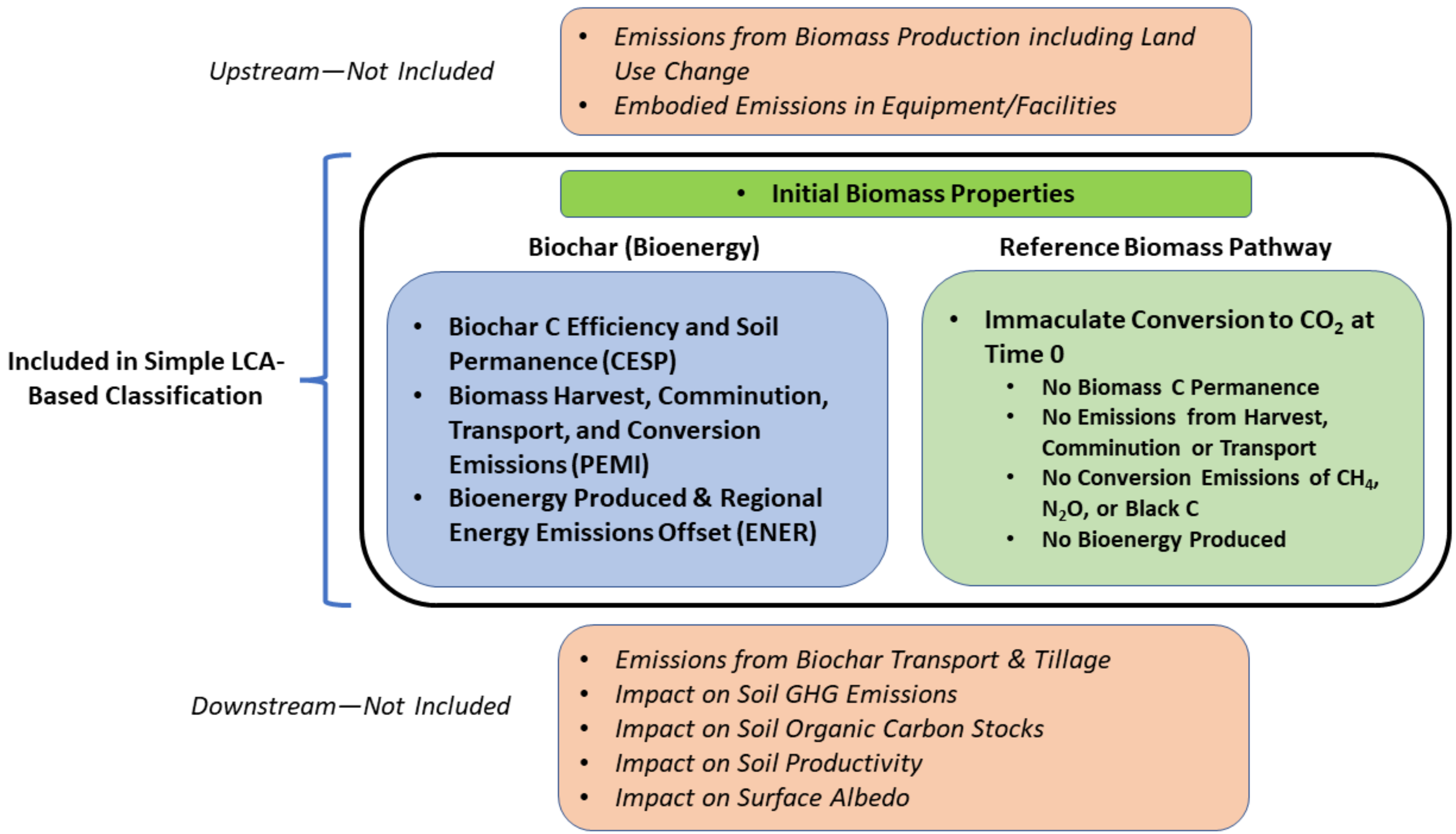

Upstream—Not Included
Emissions from Biomass Production including Land Use Change
Embodied Emissions in Equipment/Facilities
Included in Simple LCA-Based Classification
Initial Biomass Properties
Biochar (Bioenergy)
Biochar C Efficiency and Soil Permanence (CESP)
Biomass Harvest, Comminution, Transport, and Conversion Emissions (PEMI)
Bioenergy Produced & Regional Energy Emissions Offset (ENER)
Reference Biomass Pathway
Immaculate Conversion to CO_2 at Time 0
No Biomass C Permanence
No Emissions from Harvest, Comminution or Transport
No Conversion Emissions of CH_4, N_2O, or Black C
No Bioenergy Produced
Downstream—Not Included
Emissions from Biochar Transport & Tillage
Impact on Soil GHG Emissions
Impact on Soil Organic Carbon Stocks
Impact on Soil Productivity
Impact on Surface Albedo

Fig. 9.2

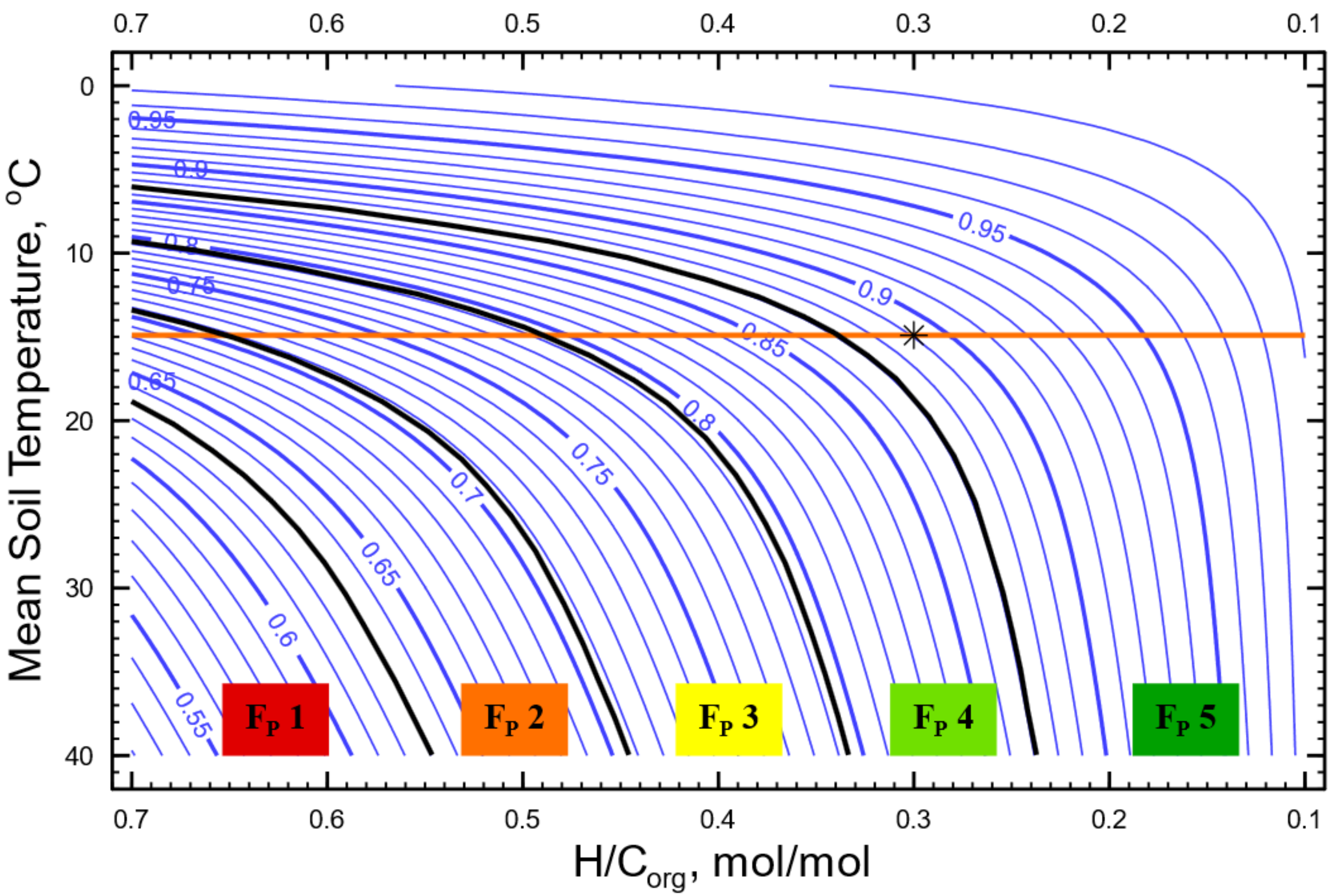
CO_2 equivalents per ton of biomass C (t CO_2e t^{-1} biomass C). To obtain the average mass of GHGAs over the 100-year period all CIs are calculated on an annual basis (Klasson and Davison, 2002, provide a thorough discussion of the dynamic LCA approach) to account for changes in the atmospheric loading of the GHGAs and the annual impacts are then averaged. A major advantage of these $CI_{XXXX}100$ parameters is that, when multiplied by the radiant efficiency of CO_2, they yield radiative forcing per ton of biomass C (Myhre et al, 2013), and thus are a fundamental (if limited) measure of CI associated with conversion of the biomass. The CI calculations are available as a workbook in the Supplementary Material that includes a user portal to allow calculations and classification determinations tailored to individual biochar production situations.

Carbon efficiency and soil persistence (CESP)

The persistence of biochar in soil is predominantly a function of intrinsic biochar properties and soil temperature (Chapter 11). The biochar property used here for CI classification purposes, is the atomic ratio of hydrogen (H) to organic C in the biochar (H/C_{org}), which estimates the degree to which the biochar C approaches a graphite-like structure (Wang et al, 2013). Values of H/C_{org} are best calculated directly from ultimate analysis results, although they can be estimated with lower accuracy from proximate analysis results (Klasson, 2017). Persistence in soil is given by the permanence factor (F_{PERM}), which is a fractional version of the BC_{+100} parameter (i.e., the proportion of organic carbon (C_{org}) in the biochar that persists in the soil for more than 100 years) used in earlier work. To calculate F_{PERM} values as a function of biochar H/C_{org} and soil temperature, two regression equations are used (Lehmann et al, 2015) relating BC_{+100} to H/C_{org} and biochar mineralization rate to temperature (Q_{10}) and coupled with temperature adjustments of mineralization rates (Woolf et al, 2021). A contour plot (Figure 9.3) shows the results of this calculation for the full range of H/C_{org} ratios (0.10 to 0.70) considered relevant and useful for C storage purposes and for the mean annual soil temperatures encountered in world soils (0 to 40°C). This plot can be used to obtain a graphical estimate of F_{PERM} in lieu of the workbook calculator in the Supplementary Material. For classification purposes, the F_{PERM} values are separated into five ranges (designated by F_p1 through F_p5, with the F_p5 class having the highest F_{PERM} values). Although the F_{PERM} values are based on correlations of BC_{+100} and H/C_{org} using a two-pool model (Lehmann et al, 2015), the corresponding single-pool rate constant ($k = -\ln(F_{PERM})/100$) is used to calculate the nominal biochar half-lives on which the F_{PERM} classification boundaries are based. These classification half-lives represent a conservative estimate of the persistence of biochar in soil (Lehmann et al, 2015). The workbook calculator (Supplementary Material) allows one to calculate F_{PERM} and related kinetic parameters (single-pool rate constant, half-life, BC_{+100}, and mean residence time) for any combination of H/C_{org} and soil temperature within these limits. In addition to H/C_{org} and temperature, other soil factors, such as moisture, texture, mineralogy, and pH (Lehmann et al, 2015; Chapter 11) can influence the persistence of biochar in soil. These other soil factors are not accounted for in the current estimates of F_{PERM}.

Figure 9.3 *Classification of biochars based on their F_{PERM} values calculated from H/C_{org} and soil temperature for the expected ranges (H/C_{org} from 0.1 to 0.7, soil temperature from 0°C to 40°C) relevant to biochar C storage in soil. Boundaries between the five classes (F_p1 through F_p5) are set by the half-life of biochar C in soil. A horizontal line marks the global mean soil temperature of 14.9°C. An asterisk marks the F_{PERM} value used in biochar production scenarios discussed below.*

While important, F_{PERM} is agnostic with respect to the method by which the biochar is produced. In the first of the three LCA-based CI estimates, $CI_{CESP}100$, the C efficiency of production (i.e., C_{eff}, the fraction of biomass C incorporated into the biochar) is combined with the C efficiency of storage in soil (i.e., F_{PERM}, the fraction of biochar C remaining after 100 years in soil). As detailed in the Supplementary Material, the calculation considers biogenic CO_2 emissions during conversion of biomass to biochar and during storage in soil (emissions of fossil-CO_2 before and during conversion and of other biogenic GHGAs during conversion are considered in calculations for $CI_{PEMI}100$). After adjusting both biogenic emission sources on an annual basis for the uptake of atmospheric CO_2 by other Earth processes (such as ocean absorption, photosynthesis, and weathering of silicate rocks), a 100-year mean value can be computed for tons CO_2 emitted per ton biomass C. A similar set of calculations for the biomass reference pathway (immaculate combustion to CO_2) yields a reference 100-year mean (2.33 t CO_2 t^{-1} biomass C) which is then subtracted from that calculated for the biochar pathway to yield the value for $CI_{CESP}100$.



Mean Soil Temperature, °C
H/C$_{org}$, mol/mol
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
0.95
0.9
0.8
0.75
0.65
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
F$_P$ 1
F$_P$ 2
F$_P$ 3
F$_P$ 4
F$_P$ 5

Fig. 9.3

A contour plot (Figure 9.4) shows $CI_{CESP}100$ values (obtained using the workbook calculator in the Supplementary Material) for the relevant ranges of C_{eff} and F_{PERM}. Also shown are the five ranges used to classify the biochars in terms of their $CI_{CESP}100$ value, with CI_{CESP} 5 having the greatest climate-mitigation impact and CI_{CESP} 1 the lowest. Classification ranges are listed in Table 9.1.

Figure 9.4 *Classification of biochars based on their $CI_{CESP}100$ values calculated from C_{eff} and F_{PERM} for the expected ranges (C_{eff} from 0.02 to 0.60, F_{PERM} from 0.52 to 1.00) relevant to biochar production and C storage in soil. An asterisk marks the $CI_{CESP}100$ value for biochar production scenarios discussed below.*

Production emissions (PEMI)

The second LCA-based CI estimate used for classification, $CI_{PEMI}100$, addresses biogenic non-CO_2 GHGA emissions during biomass conversion to biochar and fossil-CO_2 emissions associated with biomass transport, comminution, and conversion. Because the reference biomass pathway emissions will always be nil (by definition), values for $CI_{PEMI}100$ will always be positive and therefore contribute to climate change. To assess CI of biogenic emissions during conversion, measurements of production-emission factors (i.e., g X emitted kg^{-1} dry biomass) for CH_4, N_2O, and black-C particulate aerosols (BlkC) are required. In contrast, production-emission factors for fossil-CO_2 emissions are usually calculated from the amount of fossil-fuel consumed per mile or per hour of operation using standard emission factors (USEPA 2023), normalized per unit of dry biomass transported, comminuted, or converted, and then added to yield a single fossil-CO_2 production-emission factor. As detailed in the Supplementary Material, when the relevant production-emission factors are available, $CI_{PEMI}100$ values are determined by multiplying each production-emission factor by the appropriate emission-impact factor (e.g., 0.00127 for fossil CO_2, 0.125 for CH_4, 0.581 for N_2O, and 5.96 for BlkC all assuming a biomass C content of 0.50) and then summing the four products.

Acceptable values of $CI_{PEMI}100$ range from 0 to 1.00 t CO_2e t^{-1} biomass C (Table 9.1). This range is broken into quintiles, with the highest-ranking quintile (CI_{PEMI} 5) being 0 to 0.20 t CO_2e t^{-1} biomass C (indicating the smallest contribution to climate change) and the lowest-

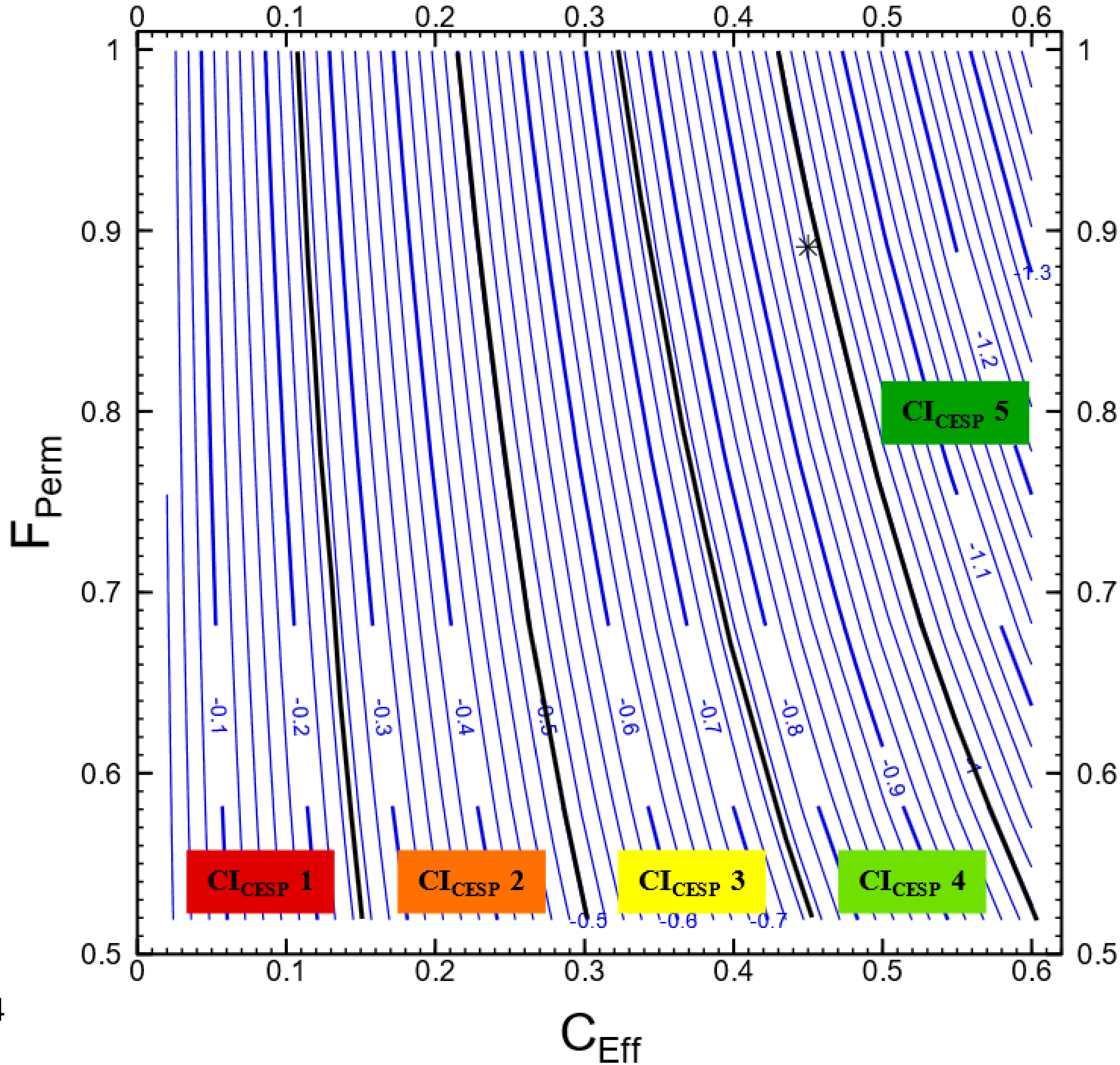


Fig. 9.4

ranking quintile (CI_{PEMI} 1) ranging from 0.80 to 1.00 t CO_2e t^{-1} biomass C. If no emissions data are collected the value of $CI_{PEMI}100$ = 0 and it is classified as "Not Rated" (shown as "?" in the workbook). Values of $CI_{PEMI}100$ greater than 1.00 t CO_2e t^{-1} biomass C are assigned a classification of "U" indicating a biochar production method that has unacceptable emission levels.

Production bioenergy (ENER)

The third LCA-based CI estimate used to classify biochar, $CI_{ENER}100$, considers the net energy recovered during the biomass conversion process that is used to offset fossil energy. As with $CI_{PEMI}100$, the reference biomass pathway emissions are nil. In contrast to $CI_{PEMI}100$, however, the value of $CI_{ENER}100$ will never be positive. If bioenergy is recovered and used to displace fossil energy, it will enhance the beneficial CI of the biochar. To estimate $CI_{ENER}100$, the maximum energy available for recovery is obtained as the difference between the energy stored in the biomass and that stored in the biochar, both on a dry mass basis. This value is multiplied by the relative energy recovery efficiency (i.e., RER_{eff}, the fraction of the potential energy that is recovered and used to displace fossil energy) and then the energy used to dry the biomass is subtracted (the biochar is bone dry) to obtain the net bioenergy recovered (and used). To complete the estimate of $CI_{ENER}100$, the net bioenergy recovered is expressed per unit of biomass C, multiplied by the C intensity of the fossil energy being displaced, and then multiplied by the mean fraction of CO_2 remaining in the atmosphere over the course of 100 years (i.e., 0.635). The energy stored in the biomass is the lower heating value (LHV), and that in the biochar is the higher heating value (HHV), both of which can either be determined experimentally or estimated using the results of an ultimate analysis (Hosokai et al, 2016; Qian et al, 2020). Similarly, the RER_{eff} may be determined experimentally (Mason et al 2021), or a generic value may be used (e.g., Woolf et al, 2010, set RER_{eff} = 0.75). Values for the C intensity of the fossil energy will vary with each situation and region. In the Supplementary Material workbook, where further details of the $CI_{ENER}100$ calculation can be found, some values for C intensity of the primary energy supply globally and in the United States are supplied, as well as for the C intensity of specific fossil fuels.

The classification quintiles for $CI_{ENER}100$ are identical to those for $CI_{CESP}100$, with the highest class (CI_{ENER} 5) being assigned for values less than -1.00 t CO_2e t^{-1} biomass C and the lowest class (CI_{ENER} 1) being assigned to values between 0 and -0.25 t CO_2e t^{-1} biomass C

(Table 9.1). There are no unacceptable values for $CI_{ENER}100$ and a value of 0 is given a "No Benefit" classification.

Biochar production climate impact (PROD)

When $CI_{CESP}100$, $CI_{PEMI}100$, and $CI_{ENER}100$ values are summed, they yield the biochar production CI ($CI_{PROD}100$), which estimates the CI of a biochar for classification purposes. Classification quintiles (Figure 9.5, Table 9.1) range from 0 to -0.30 t CO_2e t^{-1} biomass C in the lowest class (CI_{PROD} 1) to < -1.20 t CO_2e t^{-1} biomass C in the highest class (CI_{PROD} 5). If no emissions data are reported, the $CI_{PROD}100$ classification is set to "Not Rated" (shown as "?"). Reporting the classification values as CI_{PROD} X (A, B-C-D) is recommended, where X is the CI_{PROD} class and A, B, C, and D, are respectively, the classes assigned for F_{PERM}, $CI_{CESP}100$, $CI_{PEMI}100$, and $CI_{ENER}100$. For example, CI_{PROD} 4 (Fp5, 2-5-4) would represent a biochar with a $CI_{PROD}100$ value of -1.07 (Class 4), F_{PERM} value of 0.891 (Class Fp5), $CI_{CESP}100$ value of -0.33 (Class 2), $CI_{PEMI}100$ value of +0.13 (Class 5) and a $CI_{ENER}100$ value of -0.87 (Class 4). If further detail is needed, one can always report the full suite of $CI_{XXXX}100$ and F_{PERM} values.

Figure 9.5 *Classification of biochars in terms of their estimated climate impact of production based on the limited LCA-based approach. Ranges are in units of t CO_2e t^{-1} biomass C. A classification of U indicates the CI of the biochar is unacceptable and its production detracts from climate change mitigation. A classification of "?" indicates that no rating can be made because production emissions have not been considered. The estimated benefit to climate change mitigation increases with the class value, with Class 5 providing the highest benefit.*

Climate impact estimates for three biochar production scenarios

To demonstrate the application of the limited LCA-based classification system and to show the relative impacts of the three CI components, three hypothetical biochar production scenarios are considered. These use the same woody biomass feedstock and have identical C_{eff} (0.45) and F_{PERM} (0.891, corresponding to H/C_{org} of 0.3 and soil temperature of 14.9°C) values, and hence identical $CI_{CESP}100$ values, but differ in their production emissions and production bioenergy parameters. The three production scenarios are low-tech biochar production without emission controls or bioenergy capture (e.g., flame-cap kiln), modern biochar production with bioenergy production but minimal production emission controls (e.g., pyrolytic gasifier), and modern biochar production with bioenergy production and full production emission controls (e.g., a high-temperature gasifier). The production emission and bioenergy parameters for each scenario are from a project report (Amonette et al 2023) and based on published (low-tech) or proprietary data shared by manufacturers (modern) (Table 9.2). The full parameter sets for the three scenarios (Table 9.2) show large differences in production emissions with the low-tech scenario having the highest emissions of CH_4 and BlkC and lowest emissions of N_2O and fossil-CO_2.

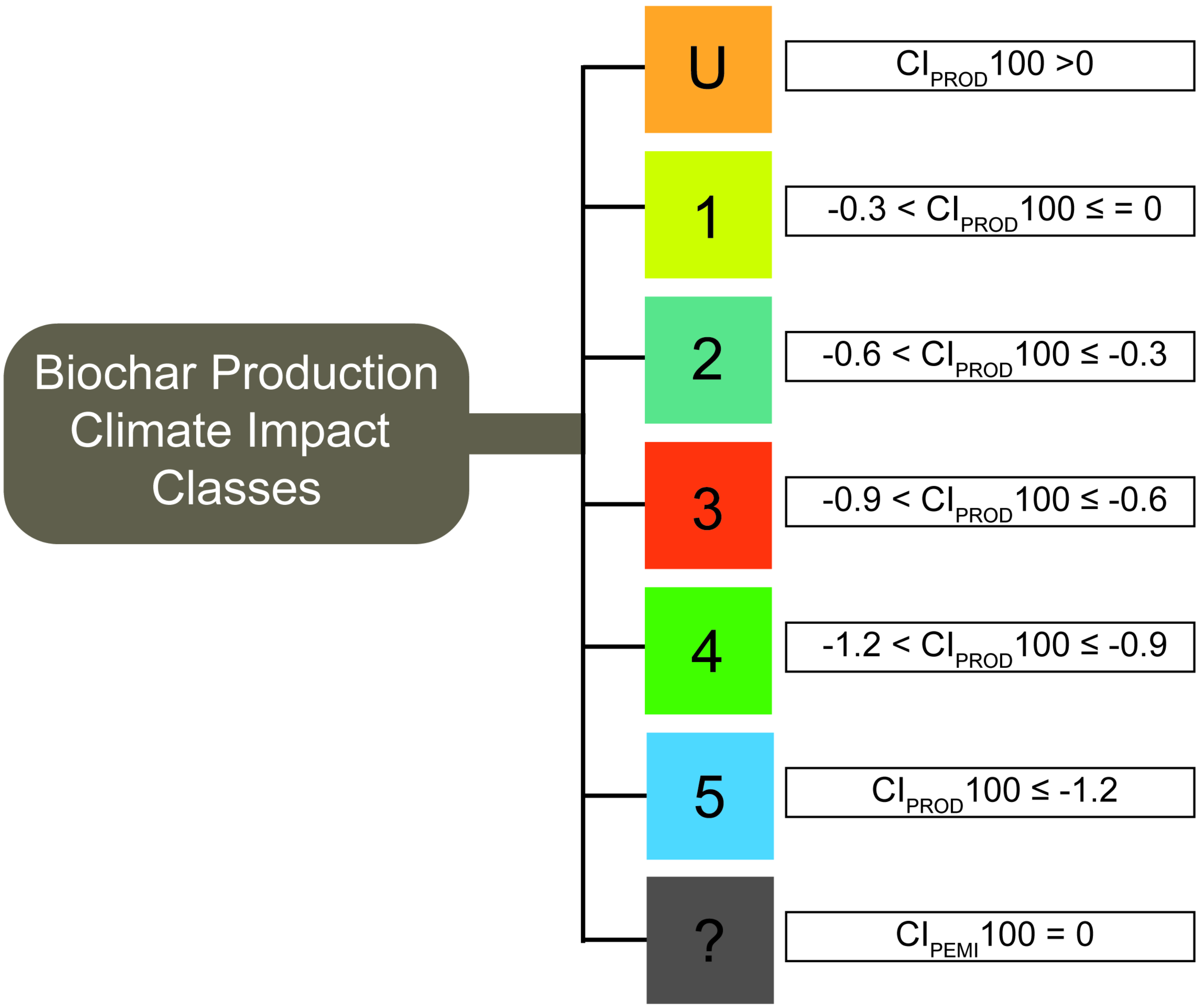
Table 9.1 *Classes for F_{perm}, for the CI components ($CI_{CESP}100$, $CI_{PEMI}100$, and $CI_{ENER}100$), and for the Biochar Production CI ($CI_{PROD}100$) assigned using the limited LCA-based classification system.*

Factor	Special classes			Classification quintiles				
	U (Unacceptable)	**?** (Not Rated)	**0** (No Benefit)	**1** (Least Benefit)	**2**	**3**	**4**	**5** (Most Benefit)
Biochar soil permanence factor, F_{PERM}	U	--	--	F_p1	F_p2	F_p3	F_p4	F_p5
Range	$F_p < 0.500$	--	--	$0.500 \leq F_p < 0.630$	$0.630 \leq F_p < 0.707$	$0.707 \leq F_p < 0.794$	$0.794 \leq F_p < 0.871$	$F_p \geq 0.871$
Criteria	$C\ t_{1/2} < 100$ y	--	--	$100\ y \leq C\ t_{1/2} < 150$ y	$150\ y \leq C\ t_{1/2} < 200$ y	$200\ y \leq C\ t_{1/2} < 300$ y	$300\ y \leq C\ t_{1/2} < 500$ y	$C\ t_{1/2} \geq 500$ y
Carbon efficiency and soil permanence, $CI_{CESP}100$	--	--	--	CI_{CESP} 1	CI_{CESP} 2	CI_{CESP} 3	CI_{CESP} 4	CI_{CESP} 5
Range (t CO_2e_{100} t^{-1} biomass C)	--	--	--	$-0.25 < CI \leq 0$	$-0.50 < CI \leq -0.25$	$-0.75 < CI \leq -0.50$	$-1.00 < CI \leq -0.75$	$CI \leq -1.00$
Production emissions, $CI_{PEMI}100$	U	?	--	CI_{PEMI} 1	CI_{PEMI} 2	CI_{PEMI} 3	CI_{PEMI} 4	CI_{PEMI} 5
Range (t CO_2e_{100} t^{-1} biomass C)	$CI \geq +1.00$	$CI = 0$	--	$+0.80 \leq CI < +1.00$	$+0.60 \leq CI < +0.80$	$+0.40 \leq CI < +0.60$	$+0.20 \leq CI < +0.40$	$0 \leq CI < +0.20$
Production bioenergy, $CI_{ENER}100$	--	--	0	CI_{ENER} 1	CI_{ENER} 2	CI_{ENER} 3	CI_{ENER} 4	CI_{ENER} 5

Range (t CO_2e_{100} t^{-1} biomass C)	--	--	CI = 0	$-0.25 < CI < 0$	$-0.50 < CI \leq -0.25$	$-0.75 < CI \leq -0.50$	$-1.00 < CI \leq -0.75$	$CI \leq -1.00$
Biochar production climate impact, $CI_{PROD}100$	U	?	--	CI_{PROD} 1	CI_{PROD} 2	CI_{PROD} 3	CI_{PROD} 4	CI_{PROD} 5
Range (t CO_2e_{100} t^{-1} biomass C)	$CI > 0$	$CI_{PEMI}100 = 0$	--	$-0.30 < CI \leq 0$	$-0.60 < CI \leq -0.30$	$-0.90 < CI \leq -0.60$	$-1.20 < CI \leq -0.90$	$CI \leq -1.20$

Factor	**Special classes**			**Classification quintiles**				
	U	**?**	**0**	**1**	**2**	**3**	**4**	**5**
	(Unacceptable)	**(Not Rated)**	**(No Benefit)**	**(Least Benefit)**				**(Most Benefit)**
Biochar soil Permanence factor, F_{PERM}	U	**--**	**--**	F_p1	F_p2	F_p3	F_p4	F_p5
Range	$F_p < 0.500$	--	--	$0.500 \leq F_p < 0.630$	$0.630 \leq F_p < 0.707$	$0.707 \leq F_p < 0.794$	$0.794 \leq F_p < 0.871$	$F_p \geq 0.871$
Criteria	C $t_{1/2} < 100$ y	--	--	100 y $\leq$ C $t_{1/2} < 150$ y	150 y $\leq$ C $t_{1/2} < 200$ y	200 y $\leq$ C $t_{1/2} < 300$ y	300 y $\leq$ C $t_{1/2} < 500$ y	C $t_{1/2} \geq 500$ y
Carbon efficiency and soil permanence, $CI_{CESP}100$	--	**--**	**--**	CI_{CESP} 1	CI_{CESP} 2	CI_{CESP} 3	CI_{CESP} 4	CI_{CESP} 5
Range (t CO_2e_{100} t^{-1} biomass C)	--	--	--	$-0.25 < CI \leq 0$	$-0.50 < CI \leq -0.25$	$-0.75 < CI \leq -0.50$	$-1.00 < CI \leq -0.75$	$CI \leq -1.00$
Production emissions, $CI_{PEMI}100e$	U	?	--	CI_{PEMI} 1	CI_{PEMI} 2	CI_{PEMI} 3	CI_{PEMI} 4	CI_{PEMI} 5

Range (t CO_2e_{100} t^{-1} biomass C)	CI ≥ +1.00	CI = 0	--	+0.80 ≤ CI < +1.00	+0.60 ≤ CI < +0.80	+0.40 ≤ CI < +0.60	+0.20 ≤ CI < +0.40	0 ≤ CI < +0.20
Production bioenergy, $CI_{ENER}100$	--	--	0	CI_{ENER} 1	CI_{ENER} 2	CI_{ENER} 3	CI_{ENER} 4	CI_{ENER} 5
Range (t CO_2e_{100} t^{-1} biomass C)	--	--	CI = 0	-0.25 < CI < 0	-0.50 < CI ≤ -0.25	-0.75 < CI ≤ -0.50	-1.00 < CI ≤ -0.75	CI ≤ -1.00
Biochar production climate impact, $CI_{PROD}100$	U	?	--	CI_{PROD} 1	CI_{PROD} 2	CI_{PROD} 3	CI_{PROD} 4	CI_{PROD} 5
Range (t CO_2e_{100} t^{-1} biomass C)	CI > 0	$CI_{PEMI}100 = 0$	--	-0.30 < CI ≤ 0	-0.60 < CI ≤ -0.30	-0.90 < CI ≤ -0.60	-1.20 < CI ≤ -0.90	CI ≤ -1.20



Biochar Production Climate Impact Classes
U
$CI_{PROD}100 > 0$
1
$-0.3 < CI_{PROD}100 \leq = 0$
2
$-0.6 < CI_{PROD}100 \leq -0.3$
3
$-0.9 < CI_{PROD}100 \leq -0.6$
4
$-1.2 < CI_{PROD}100 \leq -0.9$
5
$CI_{PROD}100 \leq -1.2$
?
$CI_{PEMI}100 = 0$

Fig. 9.5

Table 9.2 *Parameters used in the limited LCA-based approach to classifying biochars for the three examples of biochar production discussed and the results of applying the approach.*

Parameter	Biochar production method		
	Low-tech w/o energy	**Modern w/ energy**	**Modern w/ energy and full emissions control**
		------------------- Common Parameters --------------------	
Biomass C content (mass fraction)		0.50	
Biomass H_2O content (mass fraction wet basis)		0.20	
Biomass lower heating value (LHV) (GJ t^{-1} dry biomass)		18.0	
Biochar C content (mass fraction)		0.80	
Biochar H/C_{org} (mol mol^{-1})		0.3	
Biochar H_2O content (mass fraction wet basis)		nil	
Biochar higher heating value, HHV (GJ t^{-1} dry biochar		31.0	
Soil mean annual temperature (°C)		14.9	
Biochar soil permanence factor, F_{PERM} (fraction)		0.891	
Biochar production carbon efficiency[a], C_{eff} (fraction)		0.45	
Carbon intensity of primary energy supply[b] (kg CO_2 GJ^{-1})		64.11	
Alternative biomass fate		Immaculate conversion to CO_2	
		----------------------------- Production-specific parameters ------------------------------	
Relative energy recovery efficiency, RER_{eff} (fraction)	nil	0.75	0.75
		------------------------- Production-specific emission factors[c] --------------------------	
Fossil CO_2 emissions for biomass transport, comminution and conversion (g CO_2 kg^{-1} dry biomass)	25	81	44
Biogenic methane emissions (g CH_4 kg^{-1} dry biomass)	4.107	0.073	0.043
Biogenic nitrous oxide emissions (g N_2O kg^{-1} dry biomass)	0.0088	0.1850	0.1019

Biogenic black carbon emissions (g black carbon kg^{-1} dry biomass)	0.2640	0.1247	0.0015
	-------------------- 100-year climate impact (t CO_2e_{100} t^{-1} biomass C) ---------------------		
C efficiency and soil permanence, $CI_{CESP}100$	-0.98	-0.98	-0.98
Production emissions, $CI_{PEMI}100$	2.12	0.97	0.13
Production bioenergy, $CI_{ENER}100$	0.00	-0.51	-0.51
Biochar production climate impact, $CI_{PROD}100$	1.14	-0.53	-1.37
Biochar production climate impact Class	U	2	5

[a]Calculated by $(C_{BC}*m_{BC}) / (C_{BM}*m_{BM})$ where C_{XX} and m_{XX} are, respectively, the C content (g C / g XX) and total mass (g XX) of the biomass (XX = BM) converted and biochar produced (XX = BC)

[b]Data for World used by Woolf et al (2010); US mean, minimum and maximum values for 2020 are 46.87, 29.90, and 70.55 kg CO_2 GJ^{-1}, respectively, derived from https://www.eia.gov/environment/emissions/state/excel/table6.xlsx; Additional representative values for stationary combustion of specific fossil fuels are given in the Supplementary Material.

[c]Amonette et al (2023)

Using these input parameters, component CI values are assigned biochar production CI classes for each scenario using the workbook calculator (Supplementary Material). The results (Table 9.2) cover the entire range of CI classes with the low-tech scenario being classified as unacceptable (U), the modern with bioenergy as CI_{PROD} 2, and the modern with bioenergy and full emission controls as CI_{PROD} 5. The key differences are in the $CI_{PEMI}100$ values where the unacceptably large value for the low-tech scenario (+2.12) completely overwhelms the $CI_{CESP}100$ value of -0.98, that for the modern with bioenergy scenario (+0.97) cancels the $CI_{CESP}100$ value but the $CI_{ENER}100$ value of -0.51 yields a net benefit, and that for the modern with bioenergy and full production-emissions controls yields a very low $CI_{PEMI}100$ value of +0.13 (16 times smaller than for the low-tech scenario) and a robust $CI_{PROD}100$ value (-1.37). Although CH_4 is also important, the emission factor for BlkC dominates the $CI_{PEMI}100$ calculation underscoring the need to produce biochar with minimal particulate emissions (for both climate-mitigation and public-health reasons).

To show the dynamic nature of the CI calculations and to help visualize determination of the 100-year mean CI, the annualized CI_{PROD} data for the three scenarios are plotted with a zero-fill representation (Figure 9.6a). Values of CI_{PROD} greater than zero are in the "carbon-positive" region and therefore accelerate climate change relative to the biomass reference scenario, whereas those below zero are "carbon negative" (i.e., they mitigate climate change). For each scenario, the shaded area is summed (carbon-positive areas retaining a positive sign and carbon-negative areas retaining a negative sign) and then divided by 100 to obtain the $CI_{PROD}100$ result. The other three panels (Figure 9.6b, 9.6c, and 9.6d) provide annualized scenario-specific data for the component CIs and CI_{PROD}. As shown in Figures 9.6a and 9.6c for the modern with bioenergy scenario, the cross-over point between carbon positive and carbon negative for the CI_{PROD} curve represents a carbon-payback period that, in this instance, is within the 10 years considered fully sustainable (DeHue et al, 2007; DeHue 2013). In stark contrast, the carbon-payback period for the low-tech scenario is a century (Figure 9.6b), which is clearly unsustainable. The modern scenario with bioenergy and full emission controls does not have a carbon-payback period (Figure 9.6d) and therefore this scenario is fully sustainable at the time of biochar production.

Figure 9.6 *Annualized biochar production CI data for low-tech, modern with bioenergy, and modern with bioenergy and full emission controls scenarios: (a) zero-fill representation of*

CI_{PROD} data together with mean $CI_{PROD}100$ values; (b), (c), and (d) line plots of annualized CI component and CI_{PROD} data for each scenario. Dark shading above the zero line indicates the C-positive CI region. Light shading below the zero line during first ten years indicates the C-payback period during which the annualized CI_{PROD} value must become (and remain) negative for a scenario to be considered fully sustainable.

The main inference to be drawn from the incorporation of a limited LCA-based approach into the classification of the CI of biochars is that the conditions by which the biochar is produced matter greatly. The biochar properties (F_{PERM}) of the three scenarios were identical yet widely divergent $CI_{PROD}100$ values were obtained depending on GHGA emissions and production of bioenergy. Although not addressed in the scenarios, $CI_{CESP}100$ values scale directly with C_{eff}, which is far more important to the result than differences in F_{PERM} (Figure 9.7a). In the absence of bioenergy production, a biochar produced at a C_{eff} of 0.45 will have a 3-fold larger climate benefit (i.e., $CI_{CESP}100$) than one produced at a C_{eff} of 0.15. Given the current parameters included in the limited LCA-based approach, differences in C_{eff} are the next most important factor (after GHGA emissions) in determining the $CI_{PROD}100$ and become the most important factor once GHGA emissions are fully controlled (Figure 9.7b).

Figure 9.7 *Impact of biochar production C_{eff} on (a) $CI_{CESP}100$ values with different F_{PERM} values, and (b) $CI_{PROD}100$ values calculated when $F_{PERM} = 0.891$ for three biochar production scenarios having high and low production emissions of GHGAs with and without production of bioenergy.*

The ability of the workbook calculator (Supplementary Material) to classify biochars easily for their production-related CI and to discern, in general, how the individual CI components contribute to the whole CI will provide insights that help biochar production methods evolve more quickly towards those that maximize the beneficial CI of biochar production. The workbook calculator itself is expected to evolve to include a broader LCA parameter set further improving its accuracy and utility. However, while instructive and helpful for classification purposes, the limited LCA-based approach is not a substitute for a full LCA when applied to specific circumstances and considering different biomass feedstocks and reference pathways. Full LCAs are recommended for biochars whose $CI_{PROD}100$ values

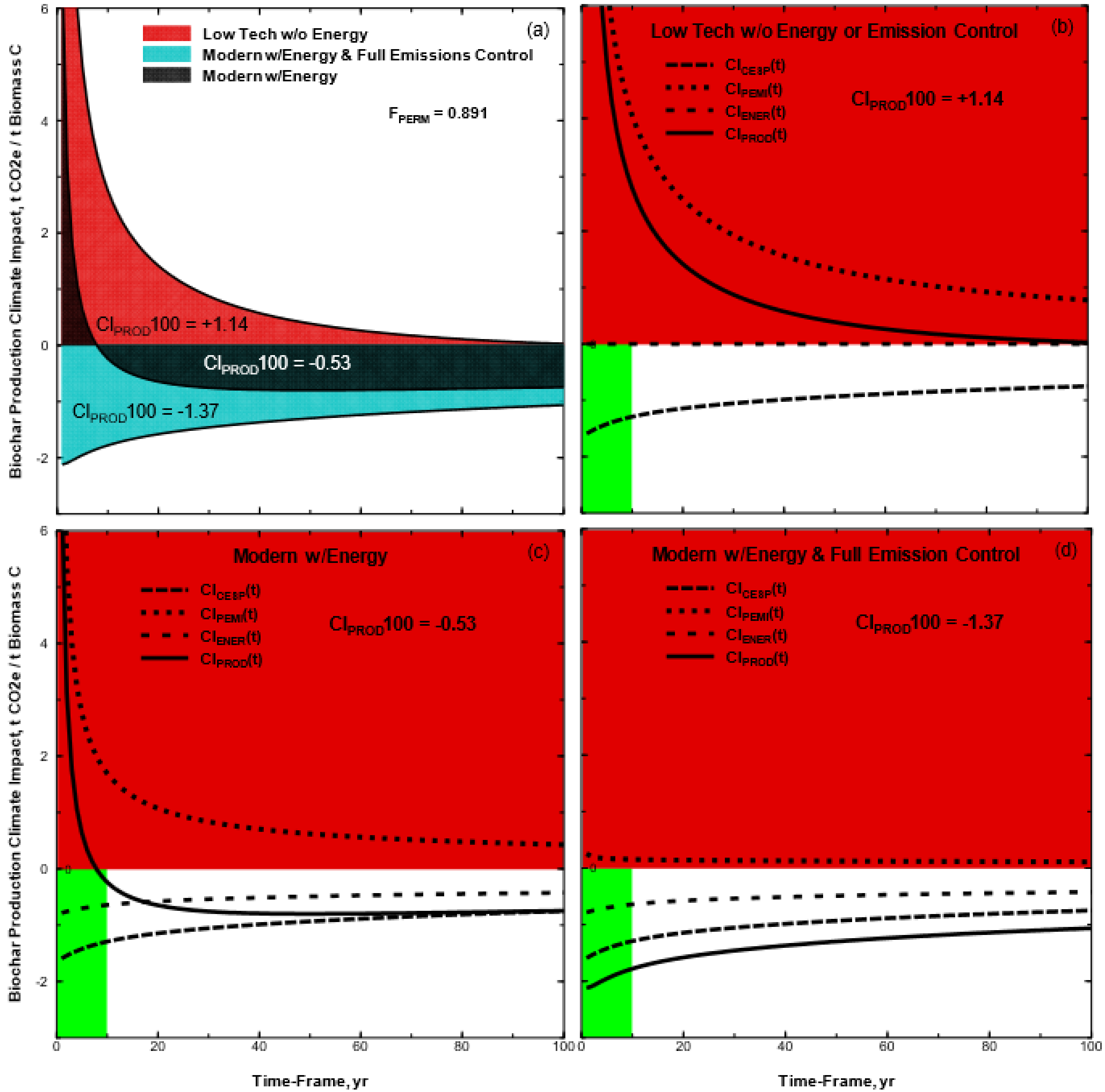
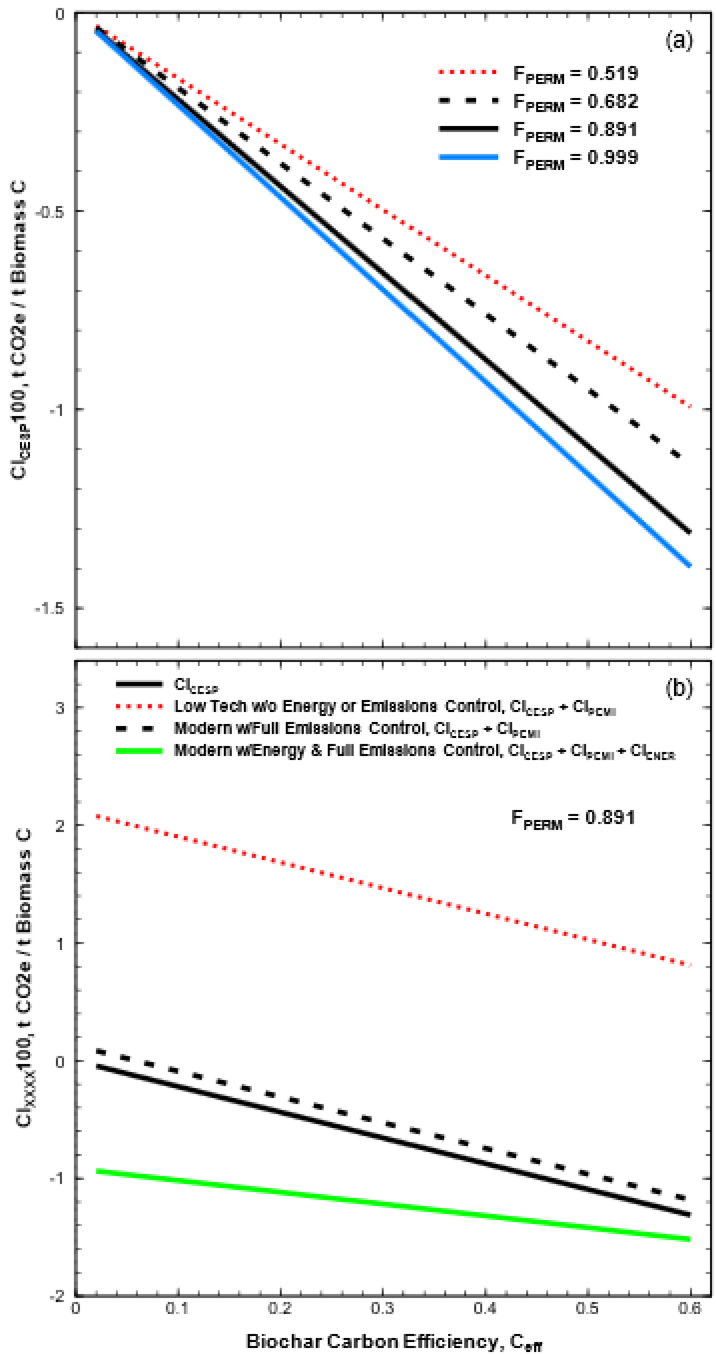

Low Tech w/o Energy
Modern w/Energy & Full Emissions Control
Modern w/Energy
(a)
F_{PERM} = 0.891
$CI_{PROD}100$ = +1.14
$CI_{PROD}100$ = -0.53
$CI_{PROD}100$ = -1.37
Low Tech w/o Energy or Emission Control
(b)
$CI_{CESP}(t)$
$CI_{PEMI}(t)$
$CI_{ENER}(t)$
$CI_{PROD}(t)$
$CI_{PROD}100$ = +1.14
Modern w/Energy
(c)
$CI_{PROD}100$ = -0.53
Modern w/Energy & Full Emission Control
(d)
$CI_{PROD}100$ = -1.37
Biochar Production Climate Impact, t CO2e / t Biomass C
Time-Frame, yr

Fig. 9.6



(a)
F_{PERM} = 0.519
F_{PERM} = 0.682
F_{PERM} = 0.891
F_{PERM} = 0.999
$CI_{CESP}100$, t CO2e / t Biomass C
0
-0.5
-1
-1.5
(b)
CI_{CESP}
Low Tech w/o Energy or Emissions Control, $CI_{CESP} + CI_{PCMI}$
Modern w/Full Emissions Control, $CI_{CESP} + CI_{PCMI}$
Modern w/Energy & Full Emissions Control, $CI_{CESP} + CI_{PCMI} + CI_{CNER}$
F_{PERM} = 0.891
$CI_{XXXX}100$, t CO2e / t Biomass C
3
2
1
0
-1
-2
0
0.1
0.2
0.3
0.4
0.5
0.6
Biochar Carbon Efficiency, C_{eff}

Fig. 9.7

classify them as U, ?, 1, and even 2, to clarify whether they truly have value for mitigation of climate change.

Supplementary Material

Supplementary material (calculator) can be found at https://s3-eu-west-1.amazonaws.com/s3-euw1-ap-pe-ws4-cws-documents.ri-prod/9781032286150/Chapter%209%20Supplementary%20Material.xlsx

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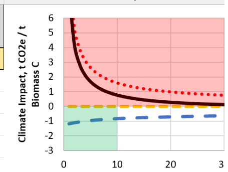
Appendix B: Images of life cycle assessment calculations for ARTi and CharBoss® scenarios.

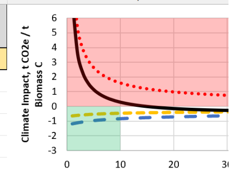
Scenario 1: ARTi pyrolytic gasifier (small Activator Kiln) without bioenergy production using biochar analysis from 23Jul2021 and C_{eff}/emission parameters from emission test of 29Jul2021

	A	B	C	D	E	F
1	INSTRUCTIONS: Enter user-defined values in green-highlighted cells in Column D, Rows 12 through 39. All other cells are protected, but can be viewed to understand their contents. Climate Impact Classification, F_{PERM} and $CI_{xxxx}100$ values display in Rows 4-8.					
3	vr16 08Aug2024	Climate Impact Classification	F_{PERM} and Climate Impact ($CI_{xxxx}100$) Values			
4	Biochar Permanence in Soil:	Fp3	F_{PERM}:	0.787	C fraction remaining after 100 yrs	
5	Carbon Efficiency & Soil Permanence:	3	$CI_{CESP}100$:	-0.577	t $CO2e_{100}$ / t biomass C	
6	Production Emissions:	1	$CI_{PEMI}100$:	0.887	t $CO2e_{100}$ / t biomass C	
7	Production Bioenergy:	0	$CI_{ENER}100$:	0.000	t $CO2e_{100}$ / t biomass C	
8	Biochar Production Climate Impact:	U	$CI_{PROD}100$:	0.310	t $CO2e_{100}$ / t biomass C	
20	2 Carbon Efficiency & Soil Permanence ($CI_{CESP}100$)	User-Defined Parameters				
21		Name	Acceptable Range	Value	Units	Comments
22		Carbon Efficiency of Production (C_{eff})	0.02 <= C_{eff} <= 1.00	0.345	--	C_{eff} = t biochar C / t biomass C
24	3 Production Emissions ($CI_{PEMI}100$)	User-Defined Parameters				
25		Name	Acceptable Range	Value	Units	Comments
26		Biomass C Content:	0.15 <= BMC <= 0.70	0.503	mass fraction, dry	
27		Fossil CO_2e Emissions:	>= 0	30.3	g CO_2e / kg dry biomass	Usually calculated for biomass transport, comminution & conversion based on fossil-f related energy use
28		Biogenic CH_4 Emissions:	>= 0	0.0745	g CH_4 / kg dry biomass	Reactor measurements
29		Biogenic N_2O Emissions:	>= 0	0.1850	g N_2O / kg dry biomass	Reactor measurements
30		Biogenic Black Carbon Emissions:	>= 0	0.1247	g Black Carbon / kg dry biomass	Reactor measurements
32	4 Production Bioenergy ($CI_{ENER}100$)	User-Defined Parameters				
33		Name	Acceptable Range	Value	Units	Comments
34		Biomass H_2O Content:	> 0	0.189	mass fraction, wet basis	
35		Biomass Lower Heating Value (LHV):	>= 0	18.53	GJ / tonne dry matter	=0.338*C + 1.223*H - 0.153*O + 0.094*S
36		Biochar C Content (BCC):	0.25 <= BCC <= 1.00	0.702	mass fraction, dry	Range adjusted for char from biosolids
37		Biochar Higher Heating Value (HHV):	>= 0	31.20	GJ / tonne dry matter	=0.329*C+1.627*H-0.162*O-9.544*S+1.408
38		Relative Energy Recovery Efficiency:	0 <= RER_{eff} <= 1.00	0.00	fraction of theoretical maximum	Woolf et al. (2010) use 0.75
39		C Intensity of Primary Energy Supply:	0 < CIntensity <= 120	45.91	kg CO_2 / GJ	See C_Intensity_Values spreadsheet



Main_User_Portal | Classification_Approach | C_Intensity_Values | Scenario_Inputs | F_Perm_Calcs v05 | CI_Calcs v02 | GWP_Calc

Scenario 2: ARTi pyrolytic gasifier (small Activator Kiln) with bioenergy production using biochar analysis from 23Jul2021 and Ceff/emission parameters from emission test of 29Jul2021.

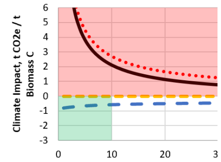


	A	B	C	D	E	F
1	INSTRUCTIONS: Enter user-defined values in green-highlighted cells in Column D, Rows 12 through 39. All other cells are protected, but can be viewed to understand their contents. Climate Impact Classification, F_{PERM} and $CI_{xxxx}100$ values display in Rows 4-8.					
2						
3	vr16 08Aug2024	Climate Impact Classification	F_{PERM} and Climate Impact ($CI_{xxxx}100$) Values			
4	Biochar Permanence in Soil:	Fp3	F_{PERM}:	0.787	C fraction remaining after 100 yrs	
5	Carbon Efficiency & Soil Permanence:	3	$CI_{CESP}100$:	-0.577	t $CO2e_{100}$ / t biomass C	
6	Production Emissions:	1	$CI_{PEMI}100$:	0.887	t $CO2e_{100}$ / t biomass C	
7	Production Bioenergy:	2	$CI_{ENER}100$:	-0.357	t $CO2e_{100}$ / t biomass C	
8	Biochar Production Climate Impact:	1	$CI_{PROD}100$:	-0.047	t $CO2e_{100}$ / t biomass C	
9						
14						
15						
16						
17						
18						
19						
20	2 Carbon Efficiency & Soil Permanence ($CI_{CESP}100$)	User-Defined Parameters				
21		Name	Acceptable Range	Value	Units	Comments
22		Carbon Efficiency of Production (C_{eff})	0.02 <= C_{eff} <= 1.00	0.345	--	C_{eff} = t biochar C / t biomass C
23						
24	3 Production Emissions ($CI_{PEMI}100$)	User-Defined Parameters				
25		Name	Acceptable Range	Value	Units	Comments
26		Biomass C Content:	0.15 <= BMC <= 0.70	0.503	mass fraction, dry	
27		Fossil CO_2e Emissions:	>= 0	30.3	g CO_2e / kg dry biomass	Usually calculated for biomass transport, comminution & conversion based on fossil-f related energy use
28		Biogenic CH_4 Emissions:	>= 0	0.0745	g CH_4 / kg dry biomass	Reactor measurements
29		Biogenic N_2O Emissions:	>= 0	0.1850	g N_2O / kg dry biomass	Reactor measurements
30		Biogenic Black Carbon Emissions:	>= 0	0.1247	g Black Carbon / kg dry biomass	Reactor measurements
31						
32	4 Production Bioenergy ($CI_{ENER}100$)	User-Defined Parameters				
33		Name	Acceptable Range	Value	Units	Comments
34		Biomass H_2O Content:	> 0	0.189	mass fraction, wet basis	
35		Biomass Lower Heating Value (LHV):	>= 0	18.53	GJ / tonne dry matter	=0.338*C + 1.223*H - 0.153*O + 0.094*S
36		Biochar C Content (BCC):	0.25 <= BCC <= 1.00	0.702	mass fraction, dry	Range adjusted for char from biosolids
37		Biochar Higher Heating Value (HHV):	>= 0	31.20	GJ / tonne dry matter	=0.329*C+1.627*H-0.162*O-9.544*S+1.408
38		Relative Energy Recovery Efficiency:	0 <= RER_{eff} <= 1.00	0.75	fraction of theoretical maximum	Woolf et al. (2010) use 0.75
39		C Intensity of Primary Energy Supply:	0 < CIntensity <= 120	45.91	kg CO_2 / GJ	See C_Intensity_Values spreadsheet
40						
41						
42						
43						

Main_User_Portal | Classification_Approach | C_Intensity_Values | Scenario_Inputs | F_Perm_Calcs v05 | CI_Calcs v02 | GWP_Calc

Scenario 3: Air Burners, Inc. CharBoss® based on BC Ceff data calc'd from dry, ash-free AZ site data in Johannesson (2024) and Montrose (2023) biogenic emissions data for Air Burners Inc. BurnBoss®

	A	B	C	D	E	F
1	INSTRUCTIONS: Enter user-defined values in green-highlighted cells in Column D, Rows 12 through 39. All other cells are protected, but can be viewed to understand their contents. Climate Impact Classification, F_{PERM} and $CI_{xxxx}100$ values display in Rows 4-8.					
2						
3	vr16 08Aug2024	Climate Impact Classification	F_{PERM} and Climate Impact ($CI_{xxxx}100$) Values			
4	Biochar Permanence in Soil:	Fp5	F_{PERM}:	0.950	C fraction remaining after 100 yrs	
5	Carbon Efficiency & Soil Permanence:	2	$CI_{CESP}100$:	-0.434	t $CO2e_{100}$ / t biomass C	
6	Production Emissions:	U	$CI_{PEMI}100$:	1.450	t $CO2e_{100}$ / t biomass C	
7	Production Bioenergy:	0	$CI_{ENER}100$:	0.000	t $CO2e_{100}$ / t biomass C	
8	Biochar Production Climate Impact:	U	$CI_{PROD}100$:	1.017	t $CO2e_{100}$ / t biomass C	
9						
14						
15						
16						
17						
18						
19						
20	2 Carbon Efficiency & Soil Permanence ($CI_{CESP}100$)	User-Defined Parameters				
21		Name	Acceptable Range	Value	Units	Comments
22		Carbon Efficiency of Production (C_{eff})	0.02 <= C_{eff} <= 1.00	0.234	--	C_{eff} = t biochar C / t biomass C
23						
24	3 Production Emissions ($CI_{PEMI}100$)	User-Defined Parameters				
25		Name	Acceptable Range	Value	Units	Comments
26		Biomass C Content:	0.15 <= BMC <= 0.70	0.503	mass fraction, dry	
27		Fossil CO_2e Emissions:	>= 0	79.1	g CO_2e / kg dry biomass	Usually calculated for biomass transport, comminution & conversion based on fossil-f related energy use
28		Biogenic CH_4 Emissions:	>= 0	0.4082	g CH_4 / kg dry biomass	Reactor measurements
29		Biogenic N_2O Emissions:	>= 0	0.1206	g N_2O / kg dry biomass	Reactor measurements
30		Biogenic Black Carbon Emissions:	>= 0	0.2106	g Black Carbon / kg dry biomass	Reactor measurements
31						
32	4 Production Bioenergy ($CI_{ENER}100$)	User-Defined Parameters				
33		Name	Acceptable Range	Value	Units	Comments
34		Biomass H_2O Content:	> 0	0.189	mass fraction, wet basis	
35		Biomass Lower Heating Value (LHV):	>= 0	18.53	GJ / tonne dry matter	=0.338*C + 1.223*H - 0.153*O + 0.094*S
36		Biochar C Content (BCC):	0.25 <= BCC <= 1.00	0.677	mass fraction, dry	Range adjusted for char from biosolids
37		Biochar Higher Heating Value (HHV):	>= 0	31.20	GJ / tonne dry matter	=0.329*C+1.627*H-0.162*O-9.544*S+1.408
38		Relative Energy Recovery Efficiency:	0 <= RER_{eff} <= 1.00	0.00	fraction of theoretical maximum	Woolf et al. (2010) use 0.75
39		C Intensity of Primary Energy Supply:	0 < CIntensity <= 120	45.91	kg CO_2 / GJ	See C_Intensity_Values spreadsheet
40						
41						
42						
43						



Main_User_Portal | Classification_Approach | C_Intensity_Values | Scenario_Inputs | F_Perm_Calcs v05 | CI_Calcs v02 | GWP_Calc