LINKING GLOBAL WARMING POTENTIAL AND ECONOMICS TO SUSTAINABILITY OF BIOCHAR USE IN HAWAIIAN AGRICULTURE

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Abstract:

Amendment of agricultural soils with biochar may sequester atmospheric carbon (C), affect soil greenhouse gas (GHG) emissions, and change crop yields; the resulting impact to agroecosystems' net global warming potential (GWP), economic feasibility, and overall sustainability is highly relevant to tropical agriculture in Hawai'i. To examine the use of biochar in Hawai'i, field trials were studied for joint assessment of GWP and economic performance. A highly fertile Mollisol and an infertile Oxisol were amended with biochar and cultivated with no-till management of bioenergy feedstock (napier grass, var. bana) and conventional tillage of a food crop (sweet corn, Hawaiian Supersweet #9). Measurement of GWP included GHG emissions and C dynamics of crop biomass, soil, and biochar. Economic assessment combined traditional benefit-cost analysis (BCA) with full-cost accounting to include environmental costs of GWP, using net present value (NPV) as a metric for sustainability. The resulting hybrid BCA was tested under alternative scenarios wherein key variables were altered. Lastly, the relative importance of these variables in determining NPV was quantified using sensitivity analysis.

Biochar amendment decreased soil GHG emissions in the Mollisol, but increased emissions in the Oxisol; concurrently, biochar increased napier grass yields by 14%, yet decreased sweet corn yields by 6%. These combined effects decreased GWP and increased NPV by as much as 73% in napier grass, resulting in a sustainable biochar system. In sweet corn, however, the best-case biochar scenario still decreased NPV by 31%—no matter how highly C was valued, corn yield decreases could not be outweighed by GWP improvements. In all, the most important factor was how biochar affected crop yields (ß=12.90±0.86), followed by GWP value (ß=10.01±1.12) and biochar investment cost (ß=7.88±0.01). For the average Hawaiian farmer, this means that investment in biochar should be carefully considered, despite its burgeoning popularity. This study showed that the best prospect for biochar amendment is for minimum-tillage crops, such as perennial bioenergy feedstocks, grown in naturally fertile soils.

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LIST OF ABBREVIATIONS

Abbreviation	Term
BCA	Benefit-cost analysis
C	Carbon
CEC	Cation-exchange capacity
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalence
CPI	Consumer price index
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DIY	Do it yourself
DOC	Dissolved organic carbon
EA	Elemental analysis
EC	European Commission
EF	Emissions factor
ESM	Equivalent soil mass
EU ETS	European Union Emissions Trading Scheme
FBM	Fish bone meal
GHG	Greenhouse gas
GWP	Global warming potential
IBI	International Biochar Initiative
IPCC	International Panel on Climate Change
K	Potassium
N	Nitrogen
N_2O	Nitrous oxide
NOAA	National Oceanic and Atmospheric Administration
NO_3^-	Nitrate
NPP	Net primary production
NPV	Net present value
NRCS	Natural Resource Conservation Service
ppmv	Parts per million by volume
RGGI	Regional Greenhouse Gas Initiative
SE	Standard error
SCC	Social cost of carbon
SOC	Soil organic carbon
SOM	Soil organic matter
tCO_2e	Metric ton carbon dioxide equivalence
US BLS	United States Bureau of Labor Statistics
USDA	United States Department of Agriculture
US EPA	United States Environmental Protection Agency
WMO	World Meteorological Organization
WUE	Water use efficiency

Chapter 1: Introduction and Background

Anthropogenic modification to the earth climate system

As Earth continues on its path through the Anthropocene, an era named for the far-reaching impacts of *Homo sapiens* on the very nature of the planet, a multitude of global environmental changes are occurring of anthropogenic origin (Vitousek et al., 1997; Zalasiewicz et al., 2010; Steffen et al., 2011). The scientific community has unearthed changes in our planet's biological, physical, and chemical nature with a profound degree of certainty owed to the systems of extraction and consumption of planetary resources that have sustained the modern global economy post-industrialization (Steffen et al., 2007; Zalasiewicz et al., 2011). Indeed, widespread anthropogenic impacts are well documented ranging from pollution of the world's oceans with microplastics (Cole et al., 2011) to alteration of the chemical composition of the planet's atmosphere (Seinfeld et al., 2012) to mass species transition and extinction in terrestrial and aquatic ecosystems (Barnosky et al., 2011). Relatively recent observations indicate changes in many characteristics of regional climate around the globe such as temperature and precipitation (IPCC, 2013a). Commonly referred to as climate change, this phenomenon is driven by anthropogenic disruption of the planet's natural cycle and storage of chemical elements that, in various gaseous forms, augment radiative forcing in the atmosphere (IPCC, 2013b). These drivers of global warming are known collectively as greenhouse gasses (GHG).

The importance of human alteration to the global carbon (C) and nitrogen (N) biogeochemical cycles cannot be overstated due to the effects on atmospheric radiative forcing of the three principal GHGs—carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—accumulating in the atmosphere at an accelerated rate. In 2013, the concentration of CO_2 in the atmosphere reached a record high annual average of 396 parts per million by volume (ppmv), compared to pre-industrial (before 1750) levels of 280 ppmv (WMO, 2013). While emissions of CO_2 far exceed that of CH_4 and N_2O, the latter two play equally as important roles due to their high relative global warming potential (GWP) compared to that of CO_2, having 34 and 298 times as much capacity for affecting radiative forcing, respectively. Atmospheric concentrations of CH_4 and N_2O are now 253% and 121%, respectively, of pre-industrial era levels (WMO, 2013). It is through these increases in concentrations of GHGs in the atmosphere that human alteration to the biogeochemical cycling of C and N plays a key role in the dynamics of global environmental change at present.

Secondary to the primary source of alteration to the global C cycle owed to the combustion of fossil C energy resources—fuels such as coal, petroleum, and natural gas—are the contributions of changing land use and management to the alteration of biogeochemical cycles (Janzen, 2004). In terrestrial ecosystems, the largest actively cycling pool of C is the soil. To a depth of one meter, the soil is thought to contain as much as 2000 Pg C (Amundson, 2001), most of which is of organic origin and sequestered in the soil via plant photosynthesis, humification, and microbial decomposition byproducts. Globally, changes in land use and management have resulted in enhanced depletion of the soil organic carbon (SOC) pool beyond its historical rate and is estimated to have contributed an additional 78 ± 12 Pg of C to the atmosphere through CO_2 gas flux from soil (Lal, 2004).

The land-use change that has most significantly impacted global SOC storage and flux is the expansion of agriculture (Houghton, 1999). A meta-analysis of data from 74 independent experiments observed that soil C stocks decline an average of 42% after land use change from forest to cropland and 59% from grassland to cropland (Guo and Gifford, 2002). A significant portion of soil C is lost due to native ecosystems being replaced by less productive ones, which results in a loss of fast-cycling C rather than older, more recalcitrant C pools (Davidson and Ackerman, 1993; Harrison et al., 1993; Trumbore et al., 1995; Stallard, 1998). Simultaneously, agricultural tillage causes substantial losses of recalcitrant C as a result of physical disturbance of soil aggregates and enhanced aeration of the soil, exposing soil organic matter (SOM) to microbes and oxidation (Tisdall and Oades, 1982; Tiessen and Stewart, 1983; Baisden et al., 2002; Ewing et al., 2006). This loss of SOC ultimately adds to the accumulation of surplus CO_2 in the atmosphere where the gas contributes to the enhancement of the planet's greenhouse warming effect, the key driver of global climate change. Enhanced addition of CH_4 to the atmosphere also comes as a result of agricultural land use and management such as rice paddy agriculture and livestock-related emissions (Ruddiman, 2007).

Also contributing to increased radiative forcing in the atmosphere is another potent GHG, N_2O. Through the phenomenon known as the N cascade, in which a molecule of reactive N is sequentially transferred from one pool to another creating detrimental effects in each reservoir, any reactive N created from non-reactive atmospheric N_2 gas has the potential to directly or indirectly affect radiative forcing and climate change as N_2O (Galloway et al., 2003). Human industrial processes like the Haber-Bosch process create reactive forms of N from non-reactive N_2. The major anthropogenic sources of N_2O include agriculture, combustion of fossil fuels, biomass burning, and atmospheric deposition of reactive N on the land and ocean surface (IPCC, 2013b).

Increased concentrations of GHGs in the atmosphere augment radiative forcing, and the ensuing warming is the mechanism that drives global climate change. Marked by shifts in long-standing averages in weather patterns around the globe, climate change poses a threat to the health and integrity of both human and non-human biological systems. Global surface temperatures have increased by 0.8°C since the nineteenth century and are projected to increase by 1.5–5.8°C over the next century (IPCC, 2013b). It has been posited that higher temperatures and other changes in climate could result in a further release of C from the soil to the atmosphere, thus creating a positive feedback loop between climate change and SOC flux. Despite much research, however, a consensus has yet to be reached regarding global net sensitivity of soil C accumulation and decomposition to changes in climate due to the complexity and spatial variability involved in such considerations at a global scale (Davidson and Janssens, 2006).

Climate change impacts and mitigation

Adverse impacts of climate change on agriculture and natural resources pose serious risk to economic and social welfare on a scale from local to global. For example, as average temperatures increase, there is high confidence that the contrast between wet and dry seasons will increase over much of the globe (IPCC, 2013b). Seasonal trends in soil moisture, precipitation, and evapotranspiration may be impacted especially greatly in the tropics and the subtropics (IPCC, 2013b). These factors combined with possible increased frequency of extreme events like floods and droughts will likely negatively impact crop yields and stress freshwater supplies in many regions of the world (IPCC, 2013c). It has been suggested that agriculture in developing nations, compared to that of developed nations, is especially vulnerable to negative impacts from climate change due to the high importance of agriculture to their economies and the scarcity of capital for responding to stresses with adaptation measures (Parry et al., 2001).

Especially relevant to the tropics, global warming has resulted in an average global sea level rise of about 20 cm since 1880, and the rise has been documented to be occurring at an accelerated rate of about 0.3 cm per year since 1993 (CSIRO, 2013; NOAA, 2014). Sea level rise poses serious risk to coastlines around the world and especially so where large populations reside at elevations close to sea level, such as tropical and subtropical island communities (Ashley et al., 2005). The resulting loss of coastal land and increased risk of flooding could strain public works infrastructure, result in property damage, and displace coastal populations, resulting in economic and social burdens to society. Additionally, climate change may likely result in direct impacts to human health associated with increases in thermal stress, extreme weather events, and infectious diseases (McMichael et al., 2006). The implications of climate change on non-human ecosystems are predicted to be negative in all future climate scenarios, indicating likely widespread increases in species extinction rates due to habitat loss and fragmentation (Thomas et al., 2004).

A number of mitigation solutions to the global climate change problem have been proposed and investigated on various scales ranging from governmental policy such as international treaties on limiting GHG emissions to engineered solutions like geological capture and storage of atmospheric CO_2. Of high interest are C pricing instruments that use economic forces to control GHG emissions, such as emissions taxation, trading, and crediting programs. In 2005, the European Commission successfully implemented the first mandatory federal C market, the European Union Emissions Trading Scheme (EU ETS), which uses the principle known as cap and trade in which a cap is set on allowed emissions of greenhouse gases (EC, 2013). Emission allowances for participating parties are either allocated or auctioned off in the form of emission credits, and credits can subsequently be traded between parties. The degree of emissions mitigation is a function of the stringency of the cap. The first market-based regulatory program concerning GHG emissions in the US is the Regional Greenhouse Gas Initiative (RGGI), which instituted a sub-national cap and trade system for CO_2 emissions from the power sector in nine states in the Northeast and Mid-Atlantic region of the US. At the state level, California's Global Warming Solutions Act of 2006 led to the establishment of the first state-mandated cap and trade program, aiming to reduce emissions to 1990 levels by 2020.

At a proper scale and level of stringency, market-based valuation of GHGs has the potential to mitigate future climate change impacts and may well be a critical mitigation strategy (Dietz and Stern, 2008). Globally, over 40 national and 20 sub-national jurisdictions have implemented market-based emissions reductions programs, covering about 12% of annual global GHG emissions (Kossoy and Guigon, 2014). Mandated participation in market valuations of C and other GHG emissions may likely emerge in greater numbers during this century at regional sub-national, national, and international levels. Additionally, the development of voluntary-participation C markets is on the rise, based on the growing demand from businesses, institutions, and individuals to willingly counteract their GHG emissions by paying for offsets. These offsets pay for projects that support the reduction of GHG emissions, such as renewable energy infrastructure, energy efficiency programs, and sustainable land use and management strategies. Such strategies include soil management practices that promote the sequestration of C from atmospheric CO_2 into the SOC pool.

Complicating institutional measures to curb GHG emissions by market-based mechanisms is the immense intricacy of the cycling of C and N within terrestrial ecosystems and, particularly when considering the integrity of C offsets funding sustainable land use and management, within the pedosphere. Verification of the validity of GHG reductions can be problematic (Lovell, 2010), and the direct measurement of soil C and N cycling dynamics is inherently challenging. For example, estimates can be made of accumulation of SOC over time under certain types of agricultural management based on computer models, but such approximations may lack full accounting for all aspects of GHG cycling within each specific system's unique local topography, biology, climate, etc. Further, the magnitude of labor and time required for C stock audits requiring visiting and monitoring field conditions at landowners' physical locations is inherently cumbersome.

Global C and N cycles and agriculture

As the largest terrestrial sink of C and a significant store of a host of other key nutrients such as N, soil is the medium for net primary production (NPP) of primary producers in terrestrial ecosystems. Plants perform the essential task of photosynthesis incorporating C from atmospheric CO_2 into their tissues while simultaneously taking up nutrients from the soil, such as reactive forms of N, through their root systems. A large portion of this NPP is eventually allocated to SOM through incorporation of plant tissues and exudates into the soil subsurface. This C- and N-rich SOM subsequently may be transformed through a number of biological, chemical, and physical processes, such as the creation of humus—the decayed amorphous fraction of SOM created by soil microorganisms. The molecular composition of SOC is hugely variable and the exact chemical species present, though perhaps overshadowed in importance by environmental factors such as climate and biology, partially determine the stability and rate of turnover of SOC fractions (Marschner et al., 2008; Kleber and Johnson, 2010; Schmidt et al., 2011). While a portion of SOC, designated as the labile fraction, is cycled back into the atmosphere as CO_2 relatively quickly and on similar terms to human timescales, another more recalcitrant fraction of SOC can have a residence time of thousands of years. Additional fractions may exist somewhere in between these extremes of labile and recalcitrant, and, in fact, our perception of fractions falling under these two labels may not even be a valuable classification scheme if one considers the persistence of C in soil across a broad spectrum as one of many ecosystem properties, all interdependent (Schmidt et al., 2011).

Soil organic carbon returns to the atmosphere as CO_2 through soil respiration, comprised of activity by soil microbes and plant roots, and is one of the largest fluxes in the C cycle at 50-80 Pg C annually (Raich and Schlesinger, 1992; Potter et al., 1993; Schimel, 1995). Soil microorganisms consume SOM and create CO_2 gas through metabolic processes. Agricultural soil management practices such as tillage increase the rate of respiration by soil microbes, augmenting this natural flux of CO_2. Soil C can also be turned over to the atmosphere as CH_4 in conditions of soil saturation, especially in rice paddy agriculture, where anoxic conditions allow for the dominance of methanogenic communities of microbes. Similarly, N_2O emissions to the atmosphere from the soil N pool occur as a result of biological nitrification of NH_4^+ to NO_3^- and subsequent denitrification of NO_3^- to gaseous N_2O by microbe metabolism. Naturally occurring fluxes of N_2O from soils are exacerbated by the widespread agricultural practices of tillage, poor irrigation management, and application of NH_3-based fertilizer, which is created from non-reactive atmospheric N_2 and combustion of fossil CH_4 through the Haber-Bosch process (Galloway et al., 2003). It is mainly through these processes that agriculture is responsible for about 80% of the anthropogenic increase in atmospheric N_2O (Kroeze et al., 1999; Davidson, 2009; Syakila and Kroeze, 2011; Zaehle et al., 2011).

In addition to loss of C and N from the soil directly to the atmosphere by gaseous flux, both nutrients can be leached from the soil by the downward movement of water through the unsaturated zone. This efflux of dissolved organic C (DOC) and N can leach further downward through the soil profile and reach the water table, where species such as nitrate (NO_3^-) can pollute groundwater. Agricultural application of both organic and inorganic N fertilizers can lead to increased leaching of N from its intended target in the plant root zone into groundwater (Galloway et al., 2003). Further, runoff of reactive N to surface waters causes eutrophication in freshwater and marine ecosystems, creating hypoxic conditions in numerous so-called "dead zones" around the world (Smith et al., 1999).

In addition to oxidized SOC fueling global warming and climate change, loss of SOC also affects soil health at the farm scale. Soil organic C is critical to the health of soil in agro-ecosystems because it has a major influence on the physical structure and the chemical nature of soil. The presence of SOC in soil increases the cation-exchange capacity (CEC), increases water-holding capacity, and promotes aggregation of soil particles (Torn et al., 2009). Loss of SOC from agricultural soils results in reduced water-holding capacity, negatively affecting crop yields as well as permitting leaching of nutrients and pesticides. Loss of SOC also diminishes soil aggregation and promotes soil erosion (Lal et al., 2003).

Strong interest exists in developing strategies for stabilizing and reducing atmospheric abundance of GHGs to mitigate the risks associated with global climate change

(Lal, 2008). Such strategies include reducing energy use through improved conservation and efficiency efforts, developing biofuels and other low-C fuel sources, and sequestering CO_2 and other GHGs using natural and engineered methods. Among options available for C sequestration, terrestrial sequestration of CO_2–C as SOC is an attractive proposition due to the numerous auxiliary benefits of C stored in soils, such as improved soil and water quality, increased crop yields, and restoration of degraded ecosystems (Lal, 2008). Pathways leading towards sequestration as SOC include sustainable soil management practices such as conservation tillage, cover cropping, diverse crop rotations, agroforestry, and integrated nutrient management (Lal, 2008).

Biofuels are renewable, bio-based liquid fuels that have the potential to partially replace petroleum-based fuels in the area of transportation energy. Depending on agricultural management practices and on biomass feedstock source, biofuels have the potential to be C-neutral and even C-negative under optimum conditions (Tilman et al., 2006), meaning that the net effect of biofuel production and consumption is that soil C sequestration from the atmosphere outweighs the amount of GHGs produced from the production system, resulting in a net negative GWP. However, biofuels produced from feedstock cultivated under poor management practices have equal potential to be ineffective and even detrimental in terms of mitigating GHG emissions (Hill et al., 2006; Searchinger et al., 2008). It is of high research priority to consider the net effect on GHG emissions and GWP of each unique biofuel production system, starting with cultivation of feedstock biomass.

Agricultural tillage practices strongly impact SOC stock, turnover, and rates of C efflux or sequestration (West and Post, 2002). Most research suggests that conservation tillage practices such as no-till result in a net decrease in soil GHG emissions by increasing sequestration of SOC (Lal and Bruce, 1999; Angers and Eriksen-Hamel, 2008; Luo et al., 2010). However, the variability in results of no-till experiments suggests that there are exceptions and subtleties to this trend and that each system must be investigated on a case-by-case basis (Luo et al., 2010; Virto et al., 2012). Overall, no-till management of cropping systems has potential for C sequestration and has been promoted as a method for reducing GHG emissions (Kong et al., 2005).

Biochar as a strategy for climate change mitigation

One such strategy for C-sequestration is the use of biochar, a C-rich charcoal substance created by the pyrolysis of biomass, as a soil amendment in agricultural systems. Woolf et al. estimated that widespread implementation of biochar production and application could result in a reduction of annual net anthropogenic emissions of GHGs in CO_2-equivalence (CO_2e) by 12% without significantly endangering global food security, habitat, or soil conservation (2010). Additionally, use of biochar in agricultural soils has been shown to have numerous ancillary benefits to overall soil health, such as improvements in water-holding capacity, nutrient-supply capacity, and soil physical properties (Ippolito et al., 2012). For example, some research has shown that NO_3^- sorbs to the positively charged surfaces of biochar, thus retaining more N in the root zone for utilization by crops and increasing yields (Kameyama et al., 2012). However, experimental observations of biochar amendment in various agricultural settings around the globe have had mixed and often contradictory results. Recent experimental results of crop yield with biochar amendment vary widely, ranging from increases in yield by up to 60% to reductions by up to 30%—now believed to be owed mainly to differences in soil characteristics across experiments (Crane-Droesch et al., 2013).

Far more certain than the effect on crop yield is that biochar is an effective agent for sequestering C in soils (Lehmann et al., 2006; Laird, 2008). Most of the C contained in biochars made at moderate and high temperatures is highly recalcitrant—stabilized against microbial decomposition due to inherent chemical properties—and hence will persist for hundreds to thousands of years when stored in soils (Ippolito et al., 2012). Additionally, the net GHG and GWP impact of biochar use is also influenced by potential changes in net primary crop productivity, efficiency of residue mineralization or humification, SOM cycling, and soil emissions of CH_4 and N_2O (Ippolito et al., 2012). For example, results of change in soil N_2O emissions as a result of biochar amendment vary widely, ranging from no change to an 80% decrease in emissions (Woolf et al., 2010). One explanation of this reduction in N_2O emissions is the sorption of soil NO_3^- to biochar surfaces (Kameyama et al., 2012). However, the unique combination of each agroecological system, biochar feedstock, and pyrolysis method will result in different outcomes; long-term field research is imperative for determining net effect of interactions of all factors on GHG emissions and GWP in each unique local production system.

A new understanding of the complex biological, chemical, and physical interactions between biochar and the greater soil environment is just beginning to emerge. It is known that soil characteristics such as fertility and degree of weathering play a major role in determing the effects of biochar application, such that highly weathered and infertile soils benefit the most from amendment with biochar (Ippolito et al., 2012). Equally as important are the varying chemical properties of different types of biochar, depending on production factors such as feedstock, heating rate, peak temperature, and thermal pretreatments (Antal and Gronli, 2003). In summary, the effects of biochar amendment to soil health, crop yields, and overall GWP mitigation is of high research priority, specifically targeting tailor-made biochar systems that account for soil type, ecosystem properties, and social and economic settings within the overall context of sustainability (Abiven et al., 2014).

Sustainable management systems

To address the sustainability of an agronomic system, tradeoffs between social, economic, and environmental factors must be considered (Figure 1.1) and specifically must be done so in common terms (Yunlong and Smit, 1994). What is good for the farmer's bottom dollar may not be good for the ecosystem or the community, and vice versa. Evaluating the triple bottom line sustainability of agricultural systems—that is to say, considering social, economic, and environmental factors equally—is critical for informing public policy and developing decision-support criteria (Robinson et al., 2012).

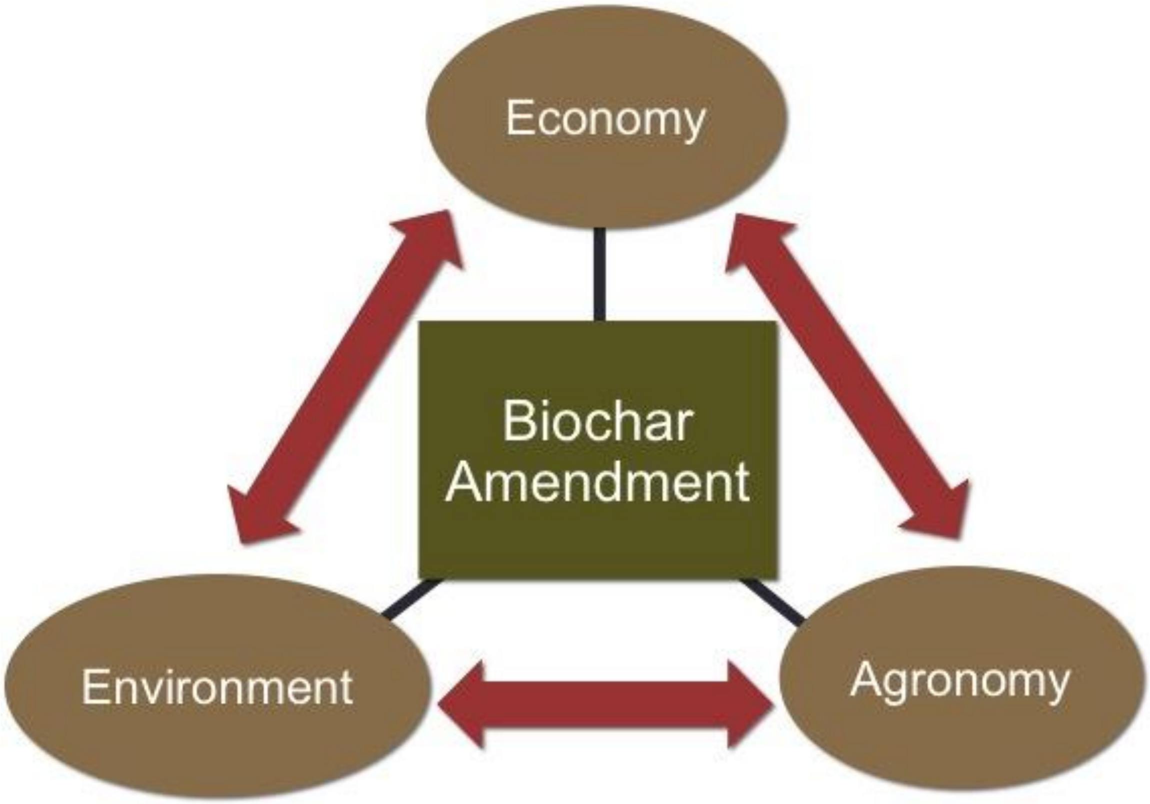

Figure 5.1. Sustainability of biochar amendment depends on system-specific environmental, economic, and agronomic factors, along with complex interactions and feedbacks between factors.

One way to quantitatively assess the feasibility of an agronomic system is to place economic value on all costs and benefits present in the system and consider the bottom-line feasibility of the system as a whole over a period of time. This method of assessment is commonly called BCA (BCA) and can measure performance over time in terms of net present value (NPV) (Lave, 1996). Taking this method one step further to account for the economic value of environmental and social externalities—which are not included in conventional agronomic BCA—is a type of full-cost accounting (Davies, 2014).

Using a full-cost accounting approach to BCA, traditional agronomic factors such as production inputs and crop yields are considered jointly with environmental and social externalities—like GHG emissions that fuel climate change—to determine the triple bottom line sustainability of the system. For example, the costs and benefits to the farmer of N fertilizer application must not be considered without equal consideration of societal costs of N_2O emissions fueling climate change (Fankhauser, 1994; Davidson, 2009). Likewise, the economic costs associated with the manufacture, transportation, and incorporation of biochar must be considered concurrently with potential benefits such as C sequestration, GHG flux mitigation, and improvements in crop yields (McCarl et al., 2009). To adequately evaluate the sustainability of an agricultural system, the full economic costs and benefits must be considered, in terms of dollars and cents, across the system as a whole.

Concurrently, clearly defining the system boundaries is also important in order to limit the scope of the analysis to a practical scale.

Considering the importance of agricultural GHG emissions contributing to global climate change (Duxbury, 1994) and the likelihood of further development of economic mechanisms for global warming mitigation such as C markets (Bernstein et al., 2010; Daskalakis et al., 2011; Kossoy and Guigon, 2012), combining BCA with full-cost accounting of net GWP can be a useful method for quantifying and comparing the sustainability of agricultural systems. By putting an economic value on the net GWP of each system, the externalities associated with fueling climate change can be accounted for in the same terms as agricultural inputs and outputs (costs and benefits). Combining the economic value of GWP with traditional costs and benefits, such as labor, fuel, soil amendments, irrigation, and crop yields, results in a novel indicator of the degree of sustainability of agricultural systems useful for comparing the relative performance of on-farm management options. Farmers could use the resulting tool as a guide for making fully informed decisions about their management practices. While GWP has been suggested for use as a method for assessing environmental soundness of agricultural systems (Robertson and Grace, 2003; Mosier et al., 2005), there are no previous studies known that have included economic valuation of the social and ecological costs of GWP as part of a farm-level agronomic BCA.

The sustainability of biochar amendment in an agronomic system depends not only on the transfer of atmospheric C into the soil C pool and overall GWP mitigation, but also on the on-farm economic viability of the biochar system. There are no studies known that have combined controlled field trials of biochar amendment with economic assessment of potential environmental and economic tradeoffs through incorporating GWP measurement and valuation into BCA. Research is needed in field-scale trials of biochar application in both food and fuel cropping systems under different soil managements, and especially amongst soils of contrasting physical and chemical properties affecting fertility.

Project objectives & hypotheses

To evaluate the sustainability of biochar amendment in agricultural systems using field trials in Hawai'i, this study had three objectives. The first objective was to build a C and N budget to quantify GWP for both biochar and control treatments in two contrasting management systems across two contrasting soil types by quantifying relevant pools and fluxes of C and N. The second objective was to assess the sustainability of biochar amendment in each system by evaluating economic, environmental, and social tradeoffs using BCA. The third objective was to test alternative scenarios for a set of key variables determinant of biochar amendment sustainability and determine the relative weights of variables in affecting the system using sensitivity analysis.

In meeting the stated objectives, three hypotheses were tested. First, it was hypothesized that (1) biochar amendment in both crops and both soils would result in a mitigation of net GWP due to (1A) direct C sequestration from incorporation of pyrolyzed C into the soil C pool, and that (1B) GHG emissions would not increase enough to significantly offset (more than 10%) the benefit of pyrolyzed C addition in the long term (10+ years).

GWP was quantified based on C and N budgets derived from field measurements and quantitative assessment of agronomic management practices of field trials. Soil CO_2, N_2O, and CH_4 fluxes were monitored in-situ for a period of 13 months.

Secondly, it was hypothesized that (2) biochar amendment in both crops would result in enhanced sustainability through (2A) increased crop yields and mitigated GWP at Waimanalo, and through (2B) increased crop yields alone at Poamoho. GWP was valued using a CO_2e price scenario. Production inputs were quantified and valued using market prices. Crop yields were measured at each harvest in field trials and valued using market prices. Overall BCA results were compared in terms of NPV as an indicator of system sustainability.

Lastly, it was hypothesized that (3) the investment cost of acquiring biochar would be the most important factor in determining the sustainability of the biochar system. Alternative scenarios of key variables were developed and tested in BCA. A sensitivity analysis was used to compare relative weights of variables in affecting NPV.

Approach

A multidisciplinary approach was taken to assess the sustainability of biochar use in Hawaiian agriculture by integrating economic, social, and environmental variables present in the system. System boundaries were, in effect, drawn around the hypothetical farm enterprise, ensuring the real-world applicability of project results and conclusions. Field trials of biochar soil amendment were carried out on Oʻahu in two crops and two soils. The system-specific physical dynamics of C and N cycling (hereafter referred to as the C and N budget) were measured in two areas: 1) flux of gaseous CO_2, CH_4, and N_2O from soil (GHG flux); and 2) changes in soil C and N stocks. In support of these biophysical measurements, further C and N budget analysis was carried out in the following three areas: 1) C sequestration from biochar amendment; 2) biofuel potential of crop biomass; and 3) on-farm GHG emissions from fossil fuel consumption.

Quantification of net GWP was based on relevant C and N budget components—namely, cumulative GHG emissions, C sequestration achieved through biochar amendment, and biofuel potential of crop biomass—plus the fossil-derived GHG emissions created by on-farm management practices.

Concurrently, economic analysis of the agronomic system was performed to calculate costs of production (inputs) and revenues from crop yields (outputs). Then, to quantify the social and environmental costs of GWP in economic terms, economic valuation of the net GWP of the system was performed. Finally, valuation of inputs, yields, and GWP were combined into a full-cost accounting BCA (Figure 1.2).

Scenarios were tested by manipulating components of the BCA in several important ways. A scenario of adjusted crop yields was considered along with actual yields obtained from field trials. Irrespective of the biochar used in field experiments, two contrasting scenarios of biochar procurement were considered. Three price scenarios were considered for valuation of GWP. Lastly, sensitivity analysis was performed to quantify the correlation between variables and the corresponding NPV from BCA.

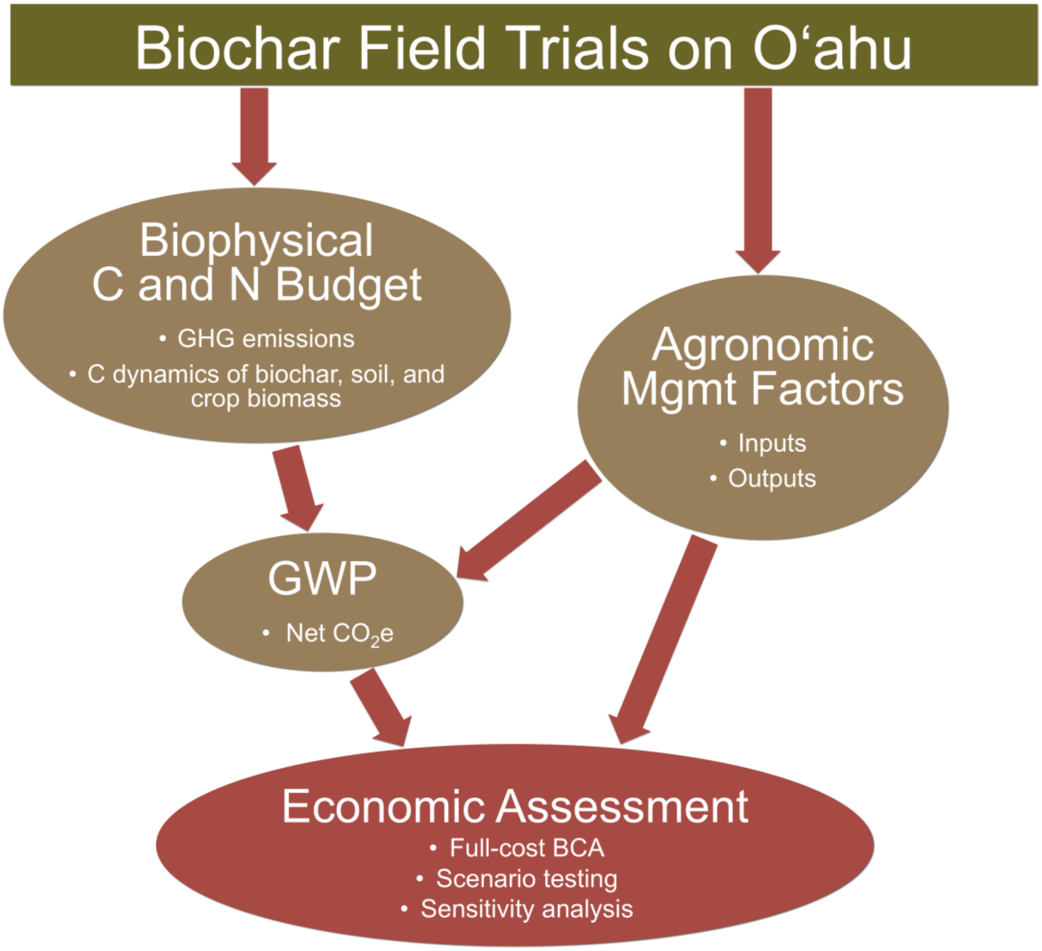

Figure 1.6. Conceptual schematic illustrating the approach used to assess sustainability of biochar as an agricultural soil amendment in Hawai'i. Conventional agronomic factors were combined with social and environmental costs of GWP into a full-cost accounting BCA.

Biochar field trials

In this research experiment, field trials of biochar amendment were carried out in two management systems within two contrasting soil types on O'ahu, Hawai'i (Figure 1.3). The objective of this experiment was to compare effects of biochar amendment on GHG flux and overall GWP of the production system, to assess economic feasibility of biochar use in both food and fuel production in Hawai'i, and to combine environmental, social, and economic performance into a novel indicator of system sustainability. The system boundaries were effectively drawn around the on-farm, field-level production system in order to ensure that the results of the project maintain real-world relevancy and practicality for farmers in Hawai'i.

Of the two soil types considered in this study, the first was a low-fertility Oxisol classified as a Wahiawa series (very-fine, kaolinitic, isohypothermic Rhodic Haplustox) with 44% clay rich in kaolinites and iron oxides, acidic reaction (pH=5.2), low CEC, located at the Poamoho Research Station. This soil series consists of deep, well-drained soils formed on residuum and alluvium weathered from basalt characterized by high manganese(2+) concentrations (NRCS, 2015). Poamoho Research Station has an elevation of 545-705 feet, average annual rainfall 35 inches, average minimum temperature 67°F, and average maximum temperature 82°F. The second soil was a fertile Mollisol classified as a Waialua series (very-fine, mixed, superactive, isohypothermic Pachic Haplustolls) with 46% clay with strong shrink-swell properties, slightly acidic (pH=6.2), moderately high CEC, high base saturation, located at the Waimanalo Research Station. This soil series consists of deep, moderately well drained soils formed in alluvium weathered from basic igneous rock (NRCS, 2015). Waimanalo Research Station has an elevation of 65-95 feet, average annual rainfall 55 inches, average minimum temperature 68°F, and average maximum temperature 82°F.

The two cropping systems investigated were sweet corn (*Zea mays*, var. super sweet #10), a food crop managed under conventional tillage with a leguminous winter cover crop (cowpea), and napier grass (*Pennisetum purpureum*, var. bana), a biofuel feedstock crop under no-till ratoon management. Both crops were managed for two harvest cycles per year. Both cropping systems had control and biochar treatments, resulting in an experimental design of 2 x 2 x 2 (two soils, two management systems, and two treatments) replicated four times and arranged in a randomized block design for a total of 32 cropped plots. Biochar treatment plots received identical management as the control plus biochar added at a rate of 1%, rounded up to about 45.4 kg of biochar per plot, in a one-time application at the beginning of the experiment. Additionally, a control bare plot was maintained in each soil and within each treatment, resulting in four additional plots of bare soil without crops equaling 36 plots total (Figure 1.4).

Based on previous research at University of Hawai'i demonstrating positive results with a low volatile matter biochar (Deenik et al., 2010; Deenik et al., 2011), biochar with low (less than 10%) volatile matter was obtained from Diacarbon Energy Inc., a manufacturer of biochar in British Columbia, Canada, and shipped to the island of Oʻahu. Feedstock for pyrolytic biochar production was 20% anaerobic digestate of agricultural sewage sludge and 80% wood chips comprised of spruce, pine, and fir trees. Elemental analysis showed that the biochar contains 81.56% C and 0.2247% N by mass.

Soils at both field sites were amended with fish bone meal (FBM) fertilizer for adequate N supply for crops. Analysis of the FBM resulted in N content of 9.07% by mass. FBM was applied at a rate of 39.1 kg per 100 square meters, resulting in 10.9 kg of FBM per plot. Napier grass received FBM once per year, while sweet corn received FBM prior to planting every crop (twice per year). Prior to cultivation, the Oxisol soil was limed at a rate of 13.6 kg per plot to pH of approximately 6.1 to match the pH of the Mollisol soil. The Oxisol soil was also amended with potash at a rate of 0.6 kg per plot for addition of sufficient potassium (K) for plant growth.

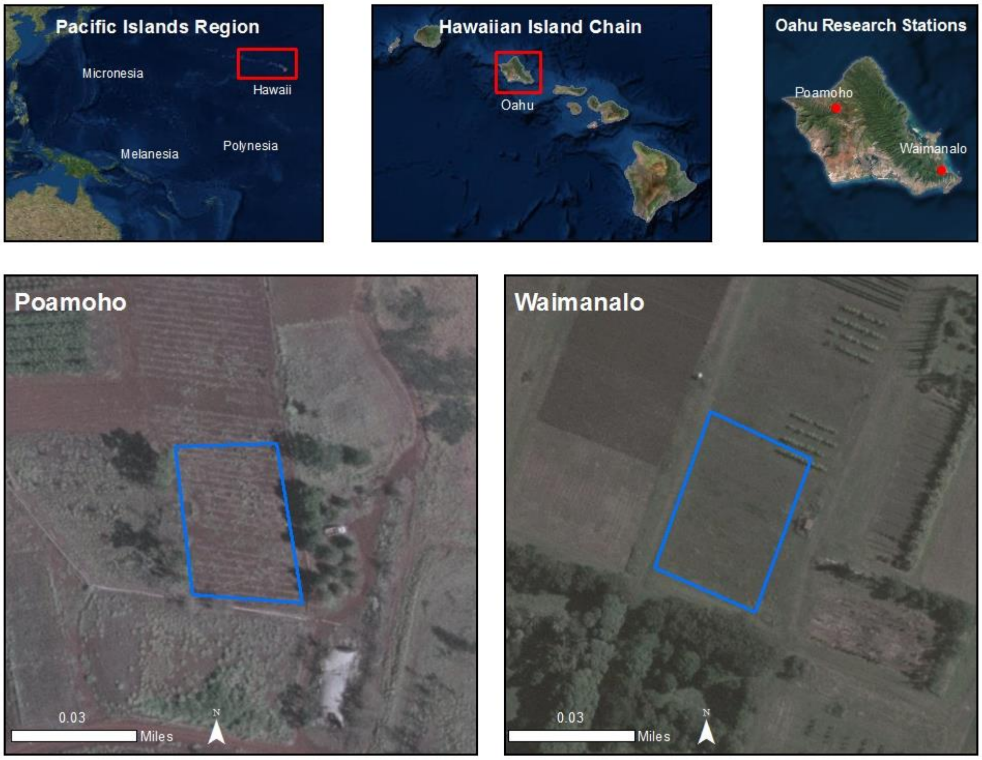

Figure 1.7. Maps of location of biochar field experiments at Poamoho and Waimanalo Research Stations on O‘ahu.

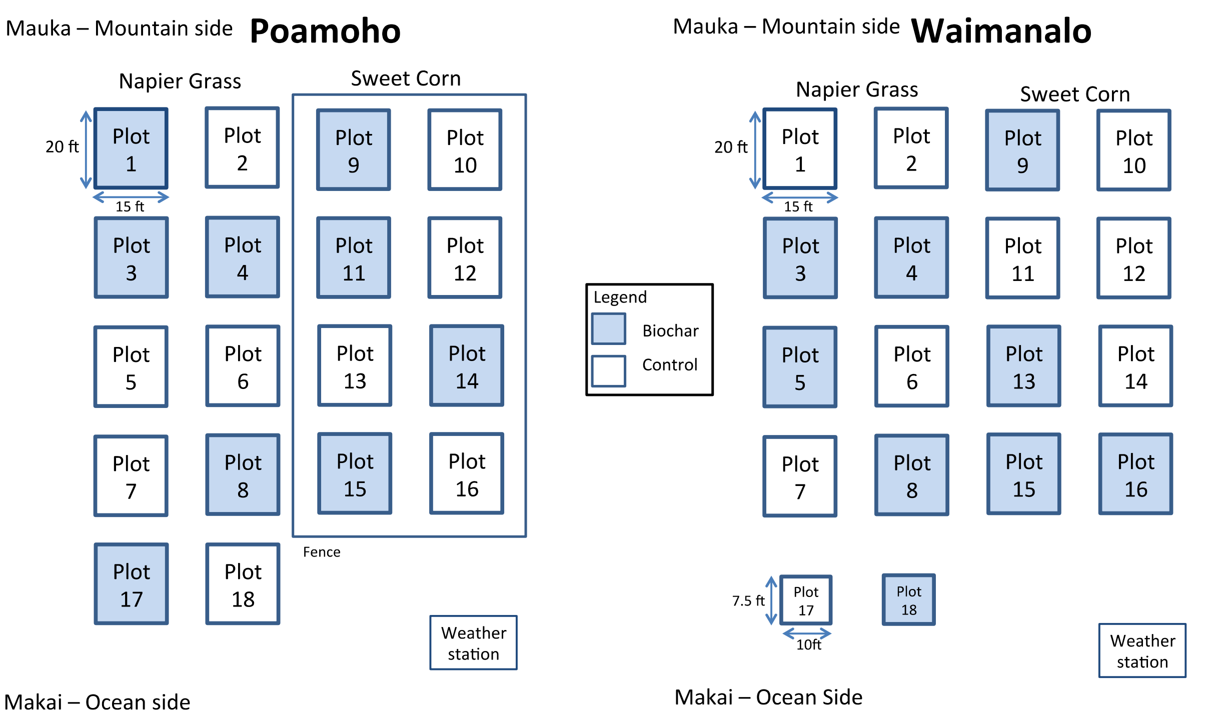

Figure 1.8. Diagrams of experimental plots at Poamoho (left) and Waimanalo (right) Research Stations.

Chapter 2: Carbon and Nitrogen Budgets

Introduction

The addition of biochar to agricultural soil may alter the C and N budget in ways that are important in terms of mitigating or exacerbating GWP. Experimental observations of biochar amendment in agricultural systems around the world have been mixed in terms of effects on crop yields and GHG emissions (Crane-Droesch et al., 2013; Ippolito et al., 2012; Woolf et al., 2010). That biochar is an effective agent for sequestering atmospheric C and transferring it into soils is a much more certain prospect due to the recalcitrant nature of pyrolyzed C (Lehmann et al., 2006; Laird, 2008). However, all three factors (crop yields, GHG emissions, and soil C sequestration) must be considered concurrently to evaluate the effect of biochar amendment on net GWP of a system.

The positive or negative outcome of biochar amendment on C and N budgets depends on factors specific to the agroecological system at hand, such as the chemical, physical, and biological properties of soils, crop physiology, and farm management practices. It is the unique combination of factors such as these that determine the overall effect of biochar on GWP for a given system (Abiven et al., 2014). To test the effects of biochar on C and N budgets that comprise GWP specifically in Hawaiian agricultural systems, field trials were carried out on Oʻahu wherein both in-situ biophysical measurements and quantitative analyses were performed. Field trials consisted of biochar amendment in two contrasting cropping systems in two contrasting soils.

Objectives & hypotheses

The objective of the work presented in this chapter was to build a C and N budget to quantify GWP for both biochar and control treatments in two contrasting crop management systems across two contrasting soil types. Greenhouse gas flux, soil C stock, crop yields, biochar C content, and fossil-fuel emissions were quantitatively assessed based on field trials. It was hypothesized that biochar amendment in both crops and both soils would result in a mitigation of net GWP due to direct C sequestration from incorporation of pyrolyzed C into the soil C pool, and that GHG emissions would not increase enough to significantly offset (more than 10%) the benefit of pyrolyzed C addition in the long term (10+ years). GWP was quantified based on C and N budgets derived from field measurements and quantitative assessment of agronomic management practices of field trials. Soil CO_2, N_2O, and CH_4 flux was monitored for a period of 13 months.

Methods

Greenhouse gas flux measurements

Soil GHG fluxes, namely CO_2, CH_4, and N_2O, were measured in-situ using fixed soil chamber methodology and a manual sampling technique. Chambers were designed to meet criteria presented in the GRACEnet protocol for chamber-based GHG monitoring (Parkin and Venterea, 2010) and constructed with cylindrical collars made of PVC plastic anchored into the soil with removable caps fitted with septa and ventilation. Installed in each plot were four chambers collars, two "wet" chambers within a crop row (therefore, along the irrigation line), and two "dry" chambers between rows (Figure 2.1). Chamber collars were installed September 2014. Monthly sampling of all plots began in October 2014 and continued for 13 months through October 2015. The 13-month sampling period captured two napier grass crops and two summer sweet corn crops, as well as one winter cover crop in the corn cropping system. Due to infeasibility of continuous GHG measurements, point-in-time field measurements were made once per month for comparison between treatments and managements. Sampling during the months of December 2014, January 2015, and February 2015 occurred on an intensified bi-weekly schedule due to a complimentary project dataset being collected simultaneously to provide a finer-resolution analysis of GHG fluxes. Sampling occurred over the one-hour period between 9:30 and 10:30 AM to capture conditions representative of average daily air temperature. At three time points in 20-minute increments immediately following cap deployment (0, 20, 40, and 60 minutes), a 6 mL gas sample was extracted from the chamber headspace using a syringe and needle and injected into a pre-evacuated 3 mL Exetainer vial.

Samples were analyzed for concentrations of the three principal GHGs by gas chromatography using a Shimadzu GC-2014 Greenhouse Gas Analyzer. Measured gas concentrations were converted to flux rates using known chamber headspace volume, soil area, and time increments. Plot-level gas fluxes were calculated as the mean of the four replicate chambers (two wet, two dry) in order to account for spatial heterogeneity of irrigation across the plot.

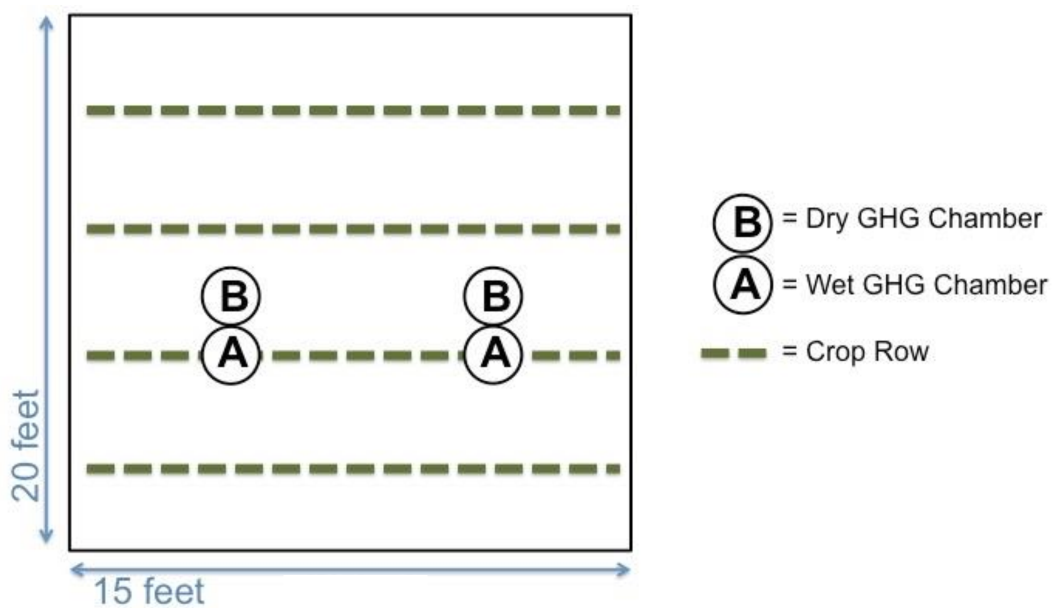

Figure 2.1. Individual field plot diagram of static GHG chamber placement within plots. Separate wet and dry chambers ensured that average plot-wide gas flux rates were captured.

Cumulative GHG emissions

Cumulative emissions of all three GHGs were calculated on an annual basis from gas flux data by extrapolating point-in-time flux measurements forwards and backwards over time to temporal midpoints between sampling dates, effectively applying a forced polynomial function to the gas flux dataset over time and calculating the area contained under (or, if negative, above) the curve. The temporal midpoints used in the calculation were then modified to account for cases in which abnormal spikes in gas fluxes were captured on a sampling date soon after occurrence of a known agronomic event, such as the application of FBM fertilizer resulting in a discrete spike in emissions, so as to not overestimate cumulative gas emissions.

Soil C stock

Soil stocks of C were measured using the equivalent soil mass (ESM) method as described by Ellert, et al. (2001). Soil samples were taken at three depth intervals from field plots using a hand auger. Samples were dried and weighed, and a subsample from each depth interval was ground to pass a 250-micron sieve for elemental analysis (EA). Samples were run on a Costech Instruments Elemental Combustion System CHNS-O model ECS 4010. Concentrations of C and N at each depth interval were converted to concentrations in an equivalent soil mass to account for spatial and temporal variability of soil bulk density. Soil C and N stock were calculated by the scaling up of equivalent soil mass concentrations to a mass per unit land area basis. Baseline stock measurements were obtained from core sampling of representative undisturbed soil adjacent to experimental plots (field trials began prior to initiation of this project) and were replicated six times within each field site. Percent soil C from true baseline sampling that occurred prior to cultivation was substituted into ESM calculations for the upper layer of soil due to inconsistency of vegetative cover of soil between sites. Soil sampling in cropped plots occurred 21 months after biochar amendment for comparison to baseline stock measurements.

Global warming potential

Quantification of field-level GWP was based on measurements of cumulative GHG emissions, C sequestration through biochar addition, biofuel potential of napier grass crop biomass, and the fossil-derived GHG emissions created by farm management practices, namely diesel-powered tractors and machinery. Positive emissions of GHGs from soil and management practices were defined as constituting positive GWP, while negative emissions of GHGs from soil, biochar amendment, and biofuel potential of crop biomass were defined as constituting negative GWP. The CO_2e comprising the biofuel potential of napier grass biomass was included as a component of GWP because, although those biofuel products were theoretically created and used off-farm, the sequestration of C from atmospheric CO_2 into terrestrial plant biomass took place in the farmer's field and, therefore, merits inclusion. For the purposes of this study, sweet corn was grown strictly as a food crop and therefore had no biofuel potential associated with it. Change in soil C stock over time measured in field measurements was not directly included in calculation of GWP due to the resulting double counting of losses of soil and/or biochar C as gaseous emissions, which would result in overestimation of GWP (i.e. soil C stock change and GHG emissions have direct overlap). Instead, known additions of biochar C and cumulative GHG emissions were used together as a more accurate evaluation that, in effect, accounted for changes in C stock indirectly.

Greenhouse gas emissions were converted to CO_2e using radiative forcing potentials relative to CO_2—34 for CH_4 and 298 for N_2O. Biochar C content was converted to CO_2e using the ratio of molecular weights of CO_2 to C, 3.667. Calculation of biofuel potential of napier grass crop biomass was done using a conversion rate of 302.8 liters ethanol per dry metric ton of crop biomass (Black & Veatch, 2010). Conversion of diesel and biofuels to CO_2e was based on conversion factors of 2.68 and 1.53 kg CO_2/liter, respectively (US EPA, 2007). All CO_2e components were summed to determine the net GWP of each management system on an annual-area basis.

Results & discussion

Greenhouse gas fluxes

Ambient fluxes (fluxes on days of a typical background state, i.e. average weather conditions and plant/soil conditions) of all three GHGs were similar between crops and between soils (Figures 2.2–2.5). Consistent with a prior assessment of the response of GHG fluxes to fertilization events in the same field trials (Biegert, 2015), amendment with FBM increased CO_2 and N_2O fluxes almost immediately after application in both crops, with peak fluxes captured 3–7 days post amendment. Clear differences between sweet corn and napier grass appeared at times of high flux events of CO_2 and N_2O following application of FBM fertilizer. At both sites, peak fluxes measured after the first FBM application were 5–10 times greater than ambient fluxes in sweet corn crops than in napier grass crops. Contrastingly, the second FBM application to sweet corn plots resulted in a spike in fluxes comparable with that of the napier grass at Waimanalo, while no coherent spike was captured in Poamoho sweet corn.

In both crops and both soils, ambient fluxes of CO_2 and N_2O were also similar between control and biochar treatments, with differences emerging at peak flux events following FBM application. Biochar treatment plots exhibited consistently higher flux rates of CO_2 and N_2O than control treatment plots immediately post-FBM across both crops and soils, with the exception of sweet corn at Waimanalo. In this case, fluxes were lower in biochar than control treatments following the first application of FBM in April 2015.

Methane fluxes in all treatments, crops, and soils were generally negative, hovering slightly below zero over the 13-month period with periodic jumps to and slightly over zero. Fluxes of CH_4 were more strongly negative in napier grass than sweet corn in both soils. In napier grass, the biochar treatment fluxes of CH_4 were less negative than in the control treatment. In biochar versus control treatments in sweet corn, CH_4 fluxes tended to be less negative at Waimanalo, but more negative at Poamoho. While napier grass at Poamoho exhibited a strongly negative spike in CH_4 flux immediately following FBM application, no consistent trend in response to FBM application was present in CH_4 fluxes across crops or soils.

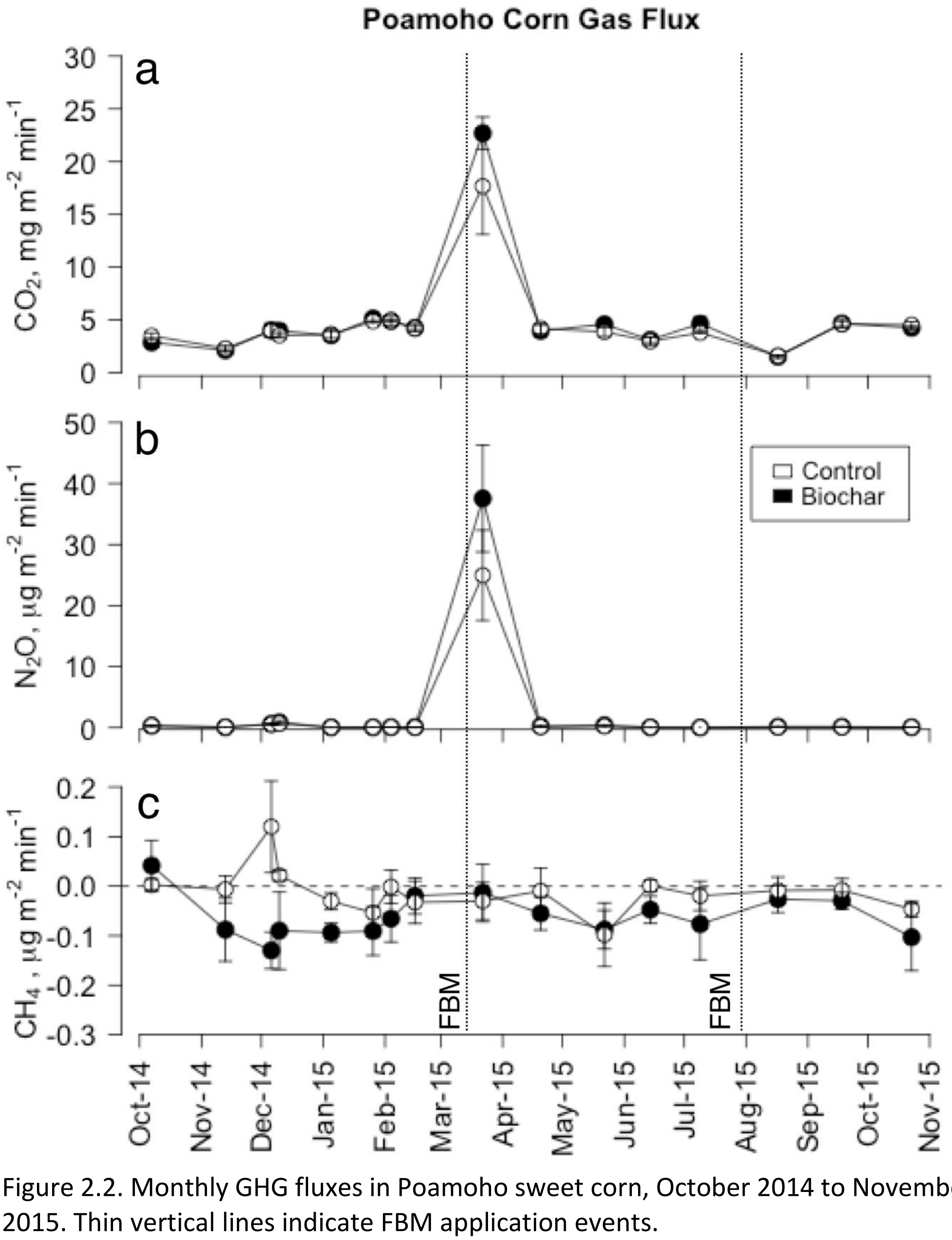

Figure 2.2. Monthly GHG fluxes in Poamoho sweet corn, October 2014 to November 2015. Thin vertical lines indicate FBM application events.

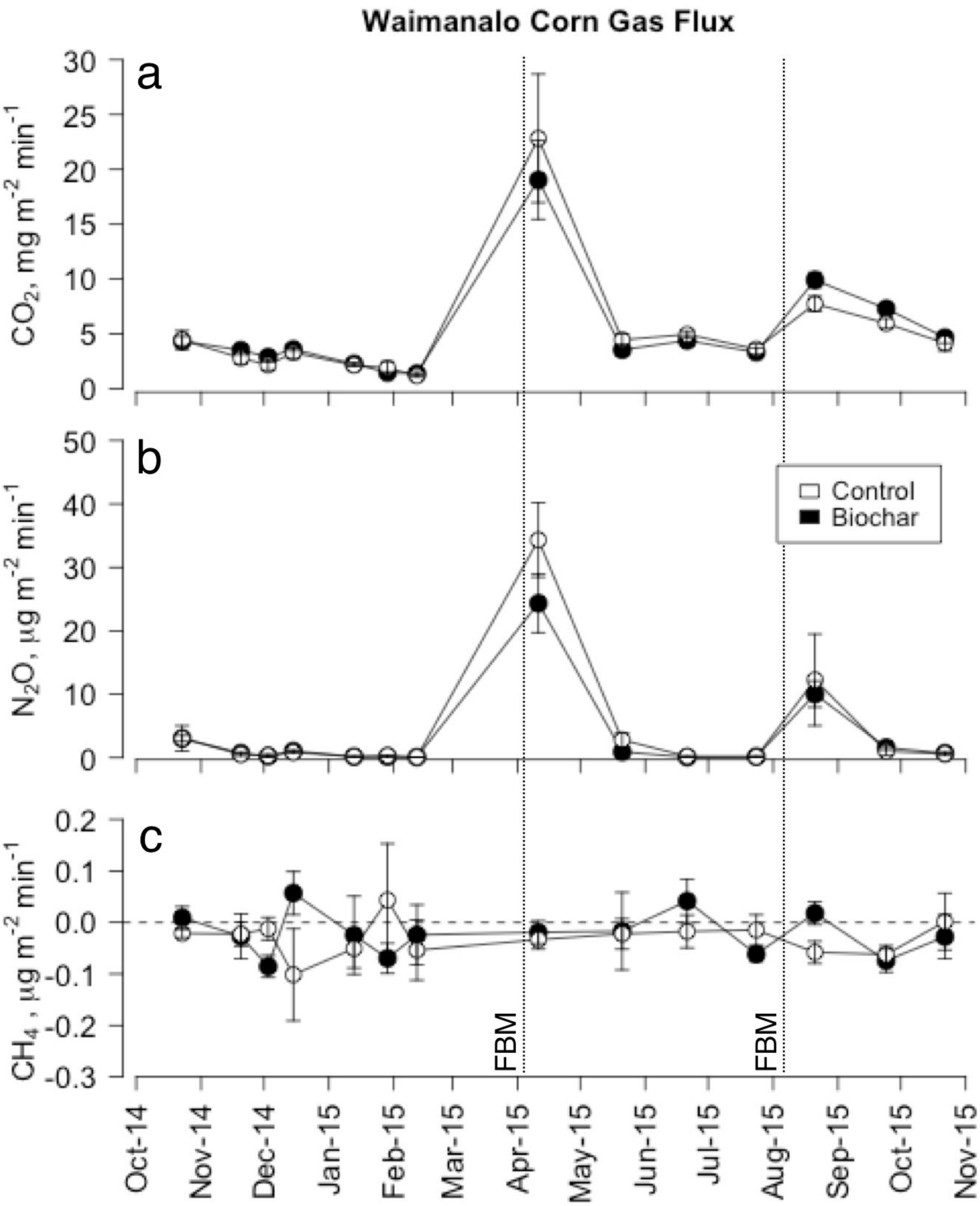

Figure 2.3. Monthly GHG fluxes in Waimanalo sweet corn, October 2014 to November 2015. Thin vertical lines indicate FBM application events.

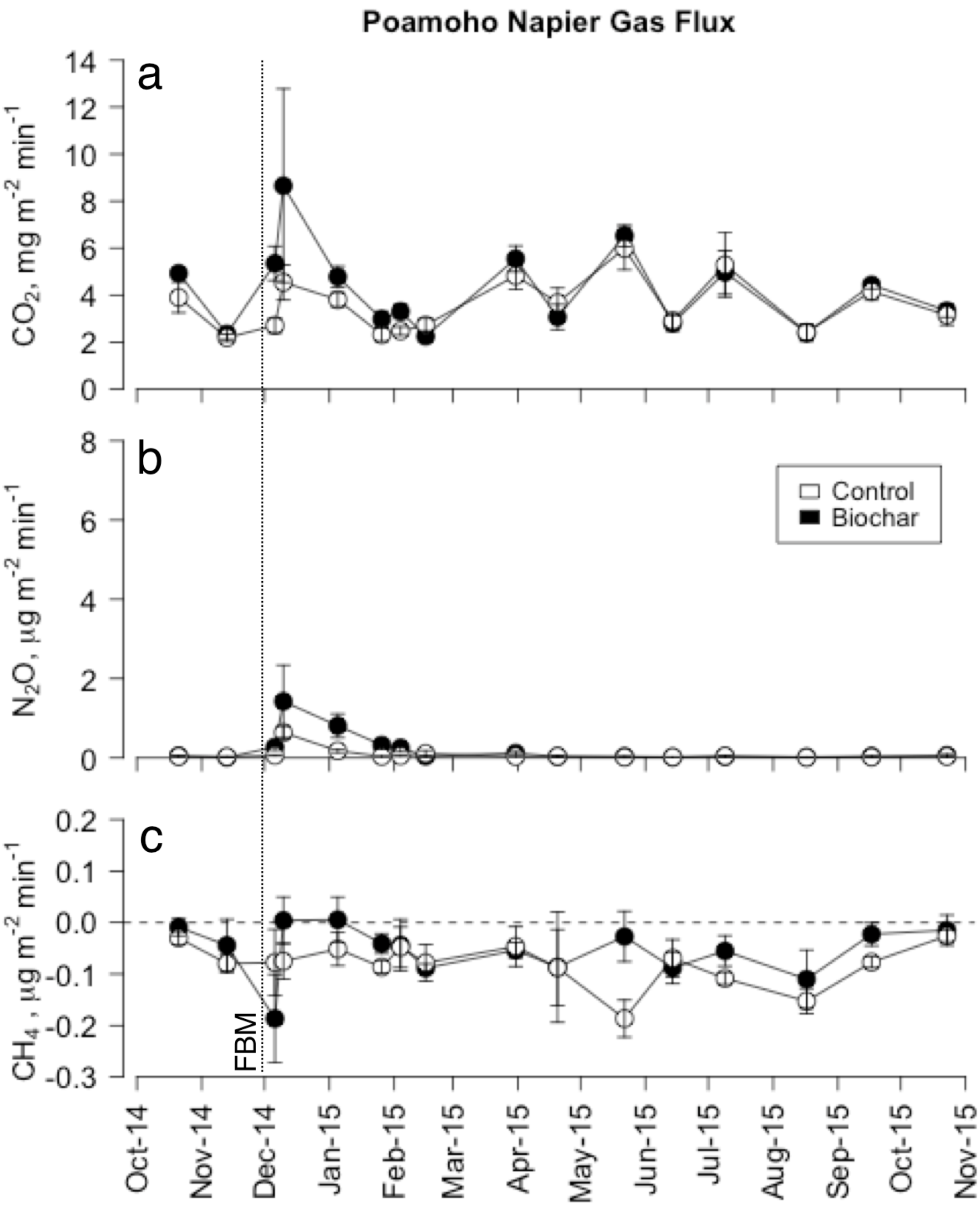

Figure 2.4. Monthly GHG fluxes in Poamoho napier grass, October 2014 to November 2015. Thin vertical lines indicate FBM application events.

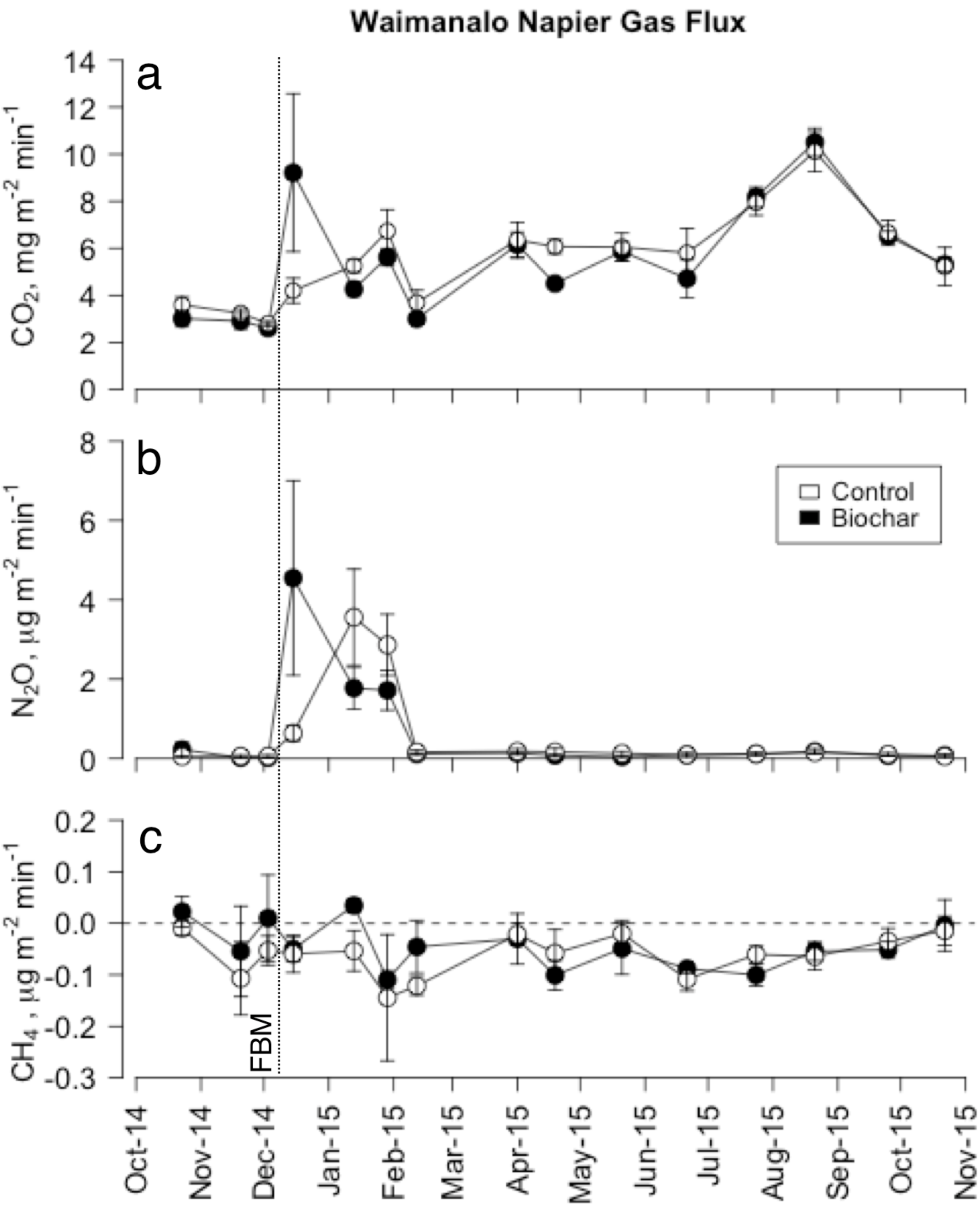

Figure 2.5. Monthly GHG fluxes in Waimanalo napier grass, October 2014 to November 2015. Thin vertical lines indicate FBM application events.

Cumulative GHG emissions

No statistical significance was found in GHG emission differences between biochar and control treatments across both sites and crops due to large amounts of variability within replicate field plots and gas measurement chambers resulting in relatively large standard errors. However, several strong trends did emerge in differences between both soil types and cropping systems, as well as some consistent trends in biochar versus control treatments within these, though not considered to be statistically significant even at $p=0.10$.

Carbon dioxide emissions tended to be lower at Poamoho compared to Waimanalo in napier grass (-20–25%) and in sweet corn (-5–10%) (Figure 2.6). Similar trends between sites were found to be true for N_2O emissions in napier grass (-60–80%) and sweet corn (-20–60%). Methane emissions were similar between sites. Between crops, CO_2 emissions were similar at Waimanalo and about 30% lower in napier grass at Poamoho. Dramatic differences were found in N_2O emissions between crops; at both sites, emissions from sweet corn plots were between 6 and 17 times the magnitude of emissions in napier grass. Methane emissions were similar between Poamoho and Waimanalo field sites and tended to be more negative in napier grass than in sweet corn.

Biochar treatment GHG emissions showed a variety of relationships with respect to the control treatment emissions with no clear general trend emerging. Though not considered statistically significant, several instances of divergence between control and biochar treatments are notable. In the case of Poamoho, both CO_2 and N_2O emissions were higher in biochar versus control treatments in both crops; CO_2 emissions were only 7–10% larger, while N_2O emissions were 53–136% higher in biochar treatment plots. Simultaneously, methane emissions from biochar versus control treatments at Poamoho were less negative in napier grass (+41%) but more negative in sweet corn (-69%). Unlike Poamoho, biochar treatment CO_2 emissions at Waimanalo were 1–3% lower than the control in both crops. Nitrous oxide emissions were slightly higher in napier grass biochar treatment (+6%), while emissions from sweet corn at the same site with biochar were 30% less than the control. In both crops at Waimanalo, CH_4 emissions were less negative in the biochar treatment (+18–39%).

In comparison, a meta-analysis of almost 300 observations of biochar amendment effects on GHG emissions showed that, in upland cultivation systems, amendment increased CO_2 emissions by 12%, but decreased N_2O emissions by 18% (Song et al., 2016). However, it has also been demonstrated that, in a high-N soil environment, biochar may increase N_2O production (Spokas and Reicosky, 2009). This may help to explain the increases in N_2O emissions observed in this study, since an N-rich environment was created in field trials with liberal additions of FBM amendment. Similarly, the identical phenomenon was observed in the case of CO_2 production when biochar was added to soils that were generously amended with both micro and macronutrients (Steiner et al, 2004). The observed tendency for biochar to increase soil respiration in this study may be due to these very factors of soil fertility. Had the soils employed in this study not been amended with FBM and potash to achieve relatively similar, robust fertility—especially in the case of the Oxisol—it is possible that no increases in soil respiration would have been observed.

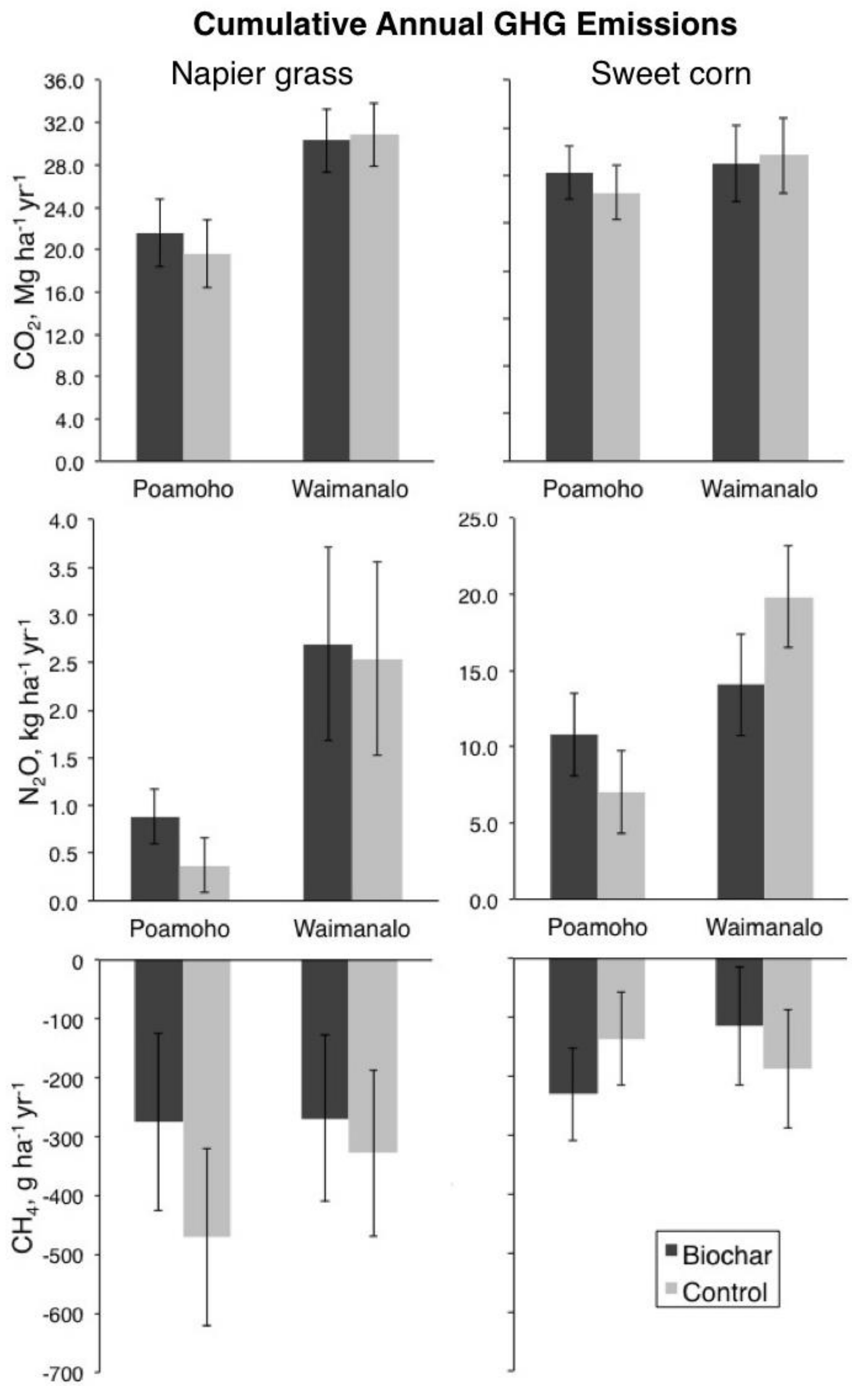

Figure 2.6. Annual cumulative GHG emissions from field trials of both crops at both sites. Note the difference in scale of the y-axis in N_2O fluxes between crops.

Soil C Stock

In the upper 6000 Mg layer of soil, baseline soil C stock was 69.81±1.80 Mg C/ha in the Poamoho Oxisol and 74.28±0.80 Mg C/ha in the Waimanalo Mollisol (Figure 2.7). At 21 months after cultivation began, biochar treatment C stock was higher than that of the control treatment in all crops by an average of about 11 Mg C/ha. At Poamoho, biochar treatment C stocks were higher than baseline by about 15%; at Waimanalo, napier grass biochar treatment C stock was 4% lower while that of sweet corn was 3% higher than baseline. Control treatment C stock at 21 months tended to be less than baseline at Waimanalo in both crops (−17%), and markedly so in sweet corn (58.83±5.48 Mg C/ha). At Poamoho, control treatments had 6% higher C stock in sweet corn and 3% lower C stock in napier grass compared to baseline soils.

Incrementally speaking, soil C stocks were largest in the top 2000 Mg mass layer of soil and decreased downward through the soil profile (Figure 2.8). The nature in which C stocks decreased with depth of soil differed between crops, treatments, and sites. Baseline C stocks were much higher in the uppermost layer of soil at Waimanalo compared to Poamoho, but site differences lessened and, although minutely, eventually reversed with increasing soil mass layer. Generally speaking, most crops and treatments at Waimanalo had sharper gradients in C stock with soil mass layer; similarly, biochar treatment resulted in increased gradients compared to control. In other words, differences between biochar and control were greatest in the uppermost soil layers and lessened downward through the profile. This observation can be attributed to the way in which biochar was tilled into the soil along with other amendments, leaving the uppermost layers of soil (to approximately 20-30 cm) enriched with high concentrations of biochar, and deeper layers relatively unaffected by biochar addition.

At both sites, but especially so at Poamoho (Figure 2.8A), differences between crops were observed with biochar treatment C stock dynamics across soil depth. In the uppermost layer of soil, napier grass C stock was higher than sweet corn, but the relationship switched in lower soil layers. This observation is evident of the contrasting tillage regimes used in the two crops; while the napier grass was not tilled after original incorporation of amendments prior to planting, sweet corn was continuously tilled throughout the 21 months of cultivation—resulting in repeated mixing of biochar C from the surface layer into deeper soil. At Waimanalo, the same circumstance was observed; with increased soil depth, sweet corn C stock decreased less sharply than napier grass.

In regards to control treatment crops, dissimilarity emerged between sites. At Poamoho, control sweet corn C stock was higher than napier grass; however, at Waimanalo, control sweet corn C stock was lower than napier grass—the lowest C stock, in fact, of all treatments, crops, and sites. This suggests that, in terms of changing soil C stock, the relative degree of importance of negative effects of continuous tillage compared to positive effects of organic matter inputs from crop residues was different between soil types. At Waimanalo, where the Mollisol had high levels of organic matter to begin with, the depleting effects of tillage (and crop cultivation in general) on soil C stock outweighed any accumulating effects of crop residues. The contrasting Oxisol at Poamoho—already low in

SOM at baseline conditions—benefited more greatly from additions of crop residues from sweet corn and the respective cover crop than the detrimental effects of tillage could compensate for. These results were captured after less than two years of cultivation—a relatively short timescale. It should, therefore, be carefully noted that whether or not these circumstances would hold true under medium- or long-term cultivation is another matter entirely.

The observed effects of biochar amendment on soil carbon stock in the Mollisol (Waimanalo), especially in the case of napier grass, were somewhat counterintuitive—and different from what is typically found in biochar experiments—in the sense that carbon stock was not increased over pre-biochar, baseline conditions. Compared to baseline, the reductions in control carbon stock indicate that the effects of tillage and crop cultivation were prevalent in diminishing soil carbon stock. Additionally, it has been found that large losses (20-53% of applied biochar) of soil-applied biochar can occur from surface runoff during intense rainfall events (Major et al., 2010), which did occur at least once during this experiment. Thus, it is possible that a loss of biochar C from the soils at Waimanalo occurred from this, for which other C-budgeting measurements carried out in this study could not account.

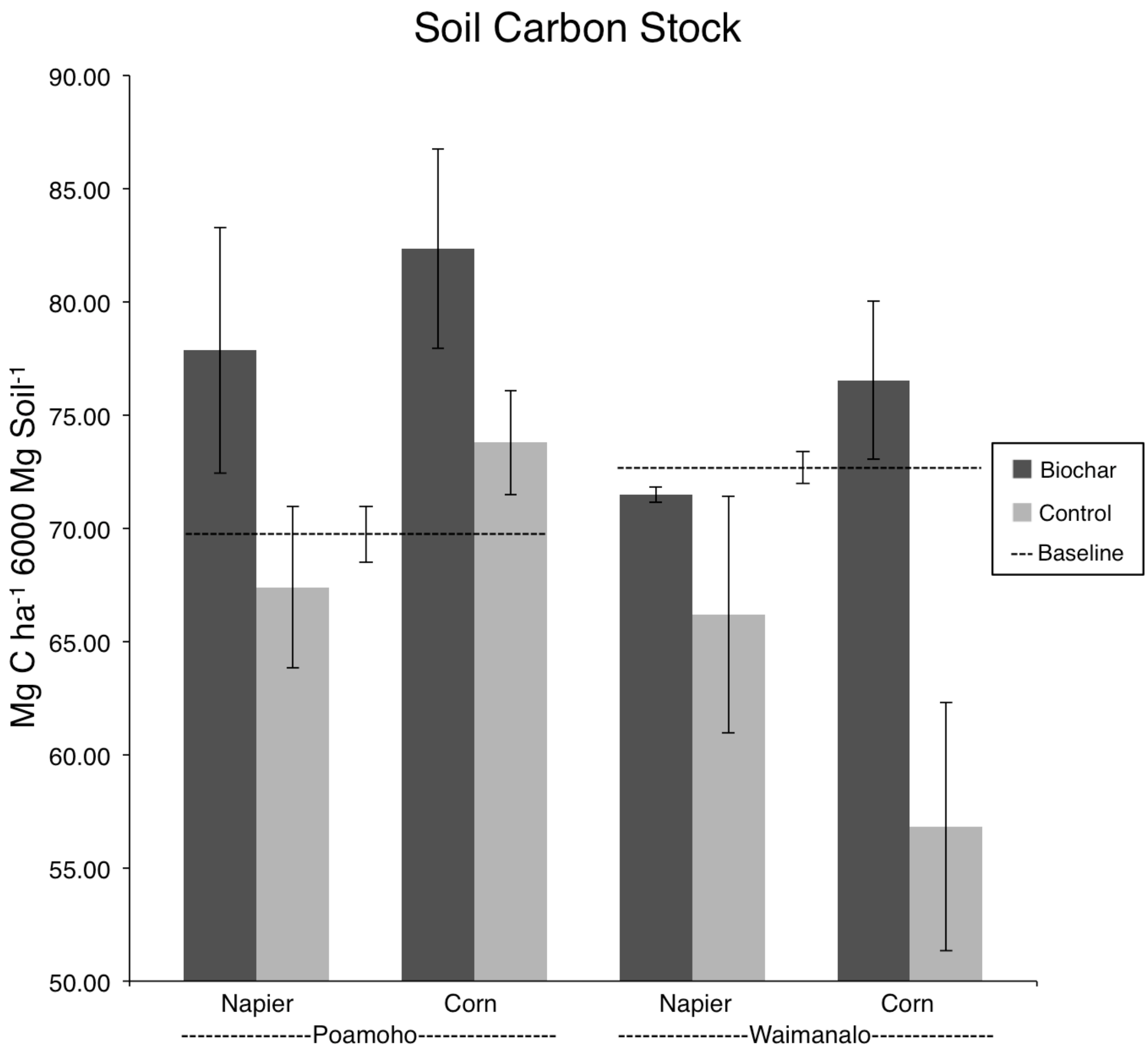

Figure 2.7. Soil C stock at 21 months after the start of field trails compared to baseline in September of 2013.

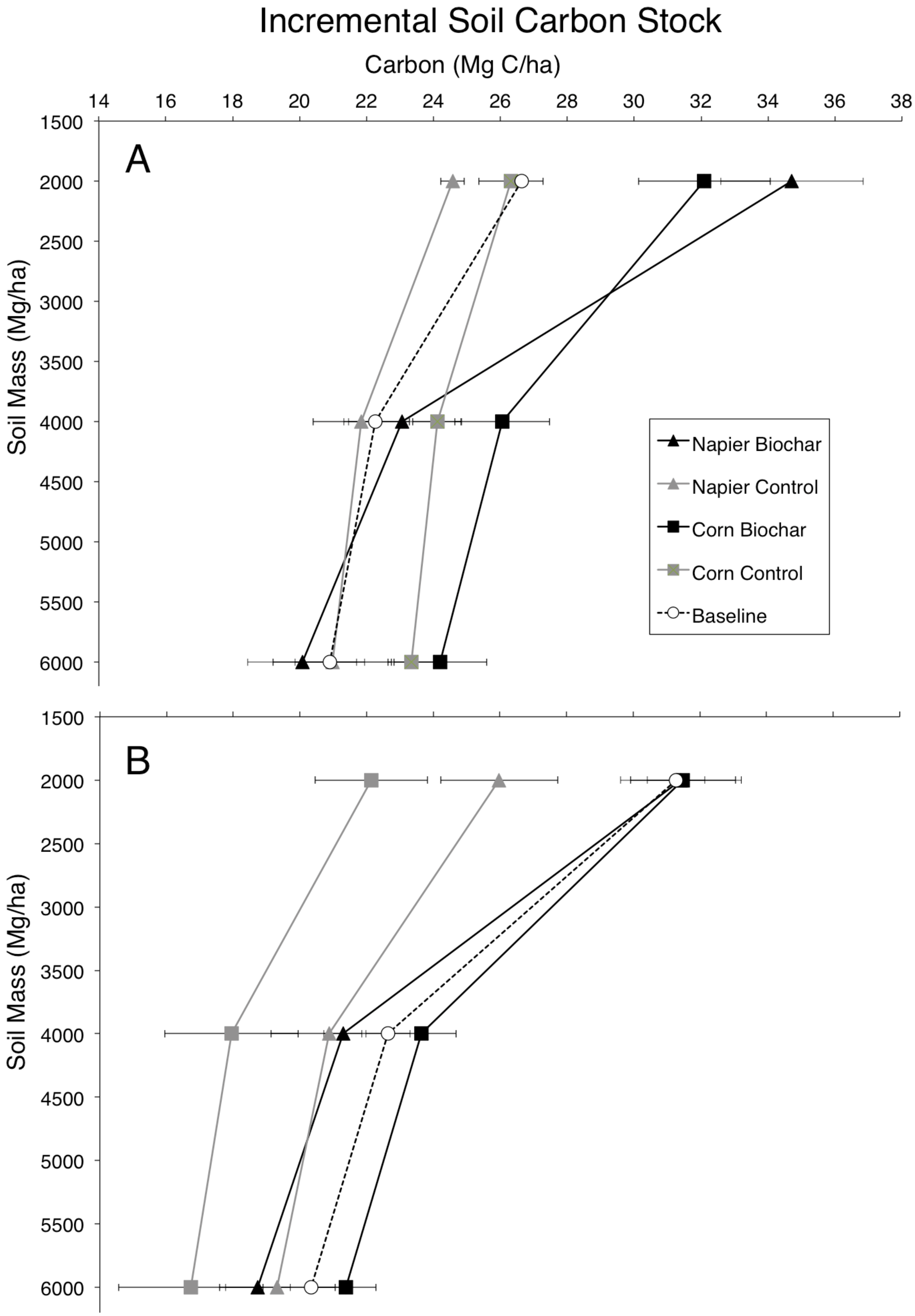

Figure 2.8. Soil C stock by incremental soil mass at Poamoho (A) and Waimanalo (B), 21 months after the start of field trials compared to baseline in September 2013.

Net GWP

Emissions of GHGs from soil were the largest source of positive GWP in the system, contributing from 19.7 to 31.6 Mg CO_2e/ha to net GWP (Figure 2.10). Waimanalo crops tended to have slightly higher GWP attributable to GHG emissions (GHG-GWP) than Poamoho, mostly due to a smaller proportion of GWP owed to emissions of N_2O, the most potent GHG of all (Figure 2.9). While 14–19% of GHG-GWP in sweet corn at Waimanalo was attributable to N_2O, the proportion was only 8–12% at Poamoho. Similar to sweet corn—although the magnitude of N_2O emissions was much small in napier grass than sweet corn—GHG-GWP in napier grass was 2-3% N_2O at Waimanalo but only about 1% at Poamoho. While emissions of CH_4 were negative, meaning that the soil was functioning as a net sink of CH_4 gas from the atmosphere, this phenomenon only offset GHG-GWP by less than 0.1% in all crops, soils, and treatments. In both treatments at both sites, the overwhelming amount of GHG-GWP was owed to emissions of CO_2; 97-99% in napier grass and 81-92% in sweet corn. Both crops at Poamoho saw an increase in GHG-GWP in biochar treatments over the control by 10%; at Waimanalo, GHG-GWP was lower in the biochar treatment by 8% in sweet corn and 2% in napier grass.

On-farm emissions of GHGs from fossil fuel combustion contributed relatively minimally to net GWP compared to soil GHG emissions, at less than 1.0 Mg CO_2e/ha in all systems. These emissions were owed to operation of a diesel-powered tractor for the purposes of soil preparation, tillage, planting, soil amendment incorporation, and harvest. The sweet corn crop management resulted in greater GWP from fossil fuels than that of the napier grass crop due to more frequent use of tractor machinery for planting and the resulting FBM amendment and tillage.

The addition of pyrolyzed biochar C to the soil resulted in a large source of negative GWP in the biochar treatment equal to 48.7 Mg CO_2e/ha, a quantity equal to between 1.5 and 2.5 the amount of positive GWP created by GHG emissions. This offsetting of positive GWP in the biochar treatment resulted in a large advantage in terms of net GWP in the biochar treatment over the control on the first year of production. In cases where a slight increase in overall GHG-GWP was recorded in the biochar treatment over the control—namely, both crops at Poamoho—it amounted to only about 5% of the reduction of CO_2e GWP achieved through biochar amendment. However, it should be noted that in year two, and every year thereafter used for the purpose of BCA, no biochar addition occurred, and therefore the benefits to net GWP of biochar amendment are limited to year one, the year in which amendment occurred. In the Poamoho Oxisol, the increased soil GHG emissions offset the GWP reduction achieved through biochar C sequestration after 17 years of sweet corn production and 23 years of napier grass production.

The biofuel potential of napier grass biomass contributed a significant amount of negative GWP to the system, on about the same scale as biochar amendment. Directly proportional to crop yields, biochar treatment napier grass contained more negative GWP from crop biofuel potential than the control treatment; similarly, the napier grass at Waimanalo exhibited a more strongly negative GWP from biofuel potential than Poamoho. Waimanalo control and biochar napier grass resulted in about 49.8 and 60.0 Mg CO_2e/ha reduction in GWP, respectively, while that of Poamoho was about 40.2 and 42.9 Mg CO_2e/ha. The large negative GWP of napier grass biomass due to its biofuel potential results in an advantage in terms of net GWP over the sweet corn crop.

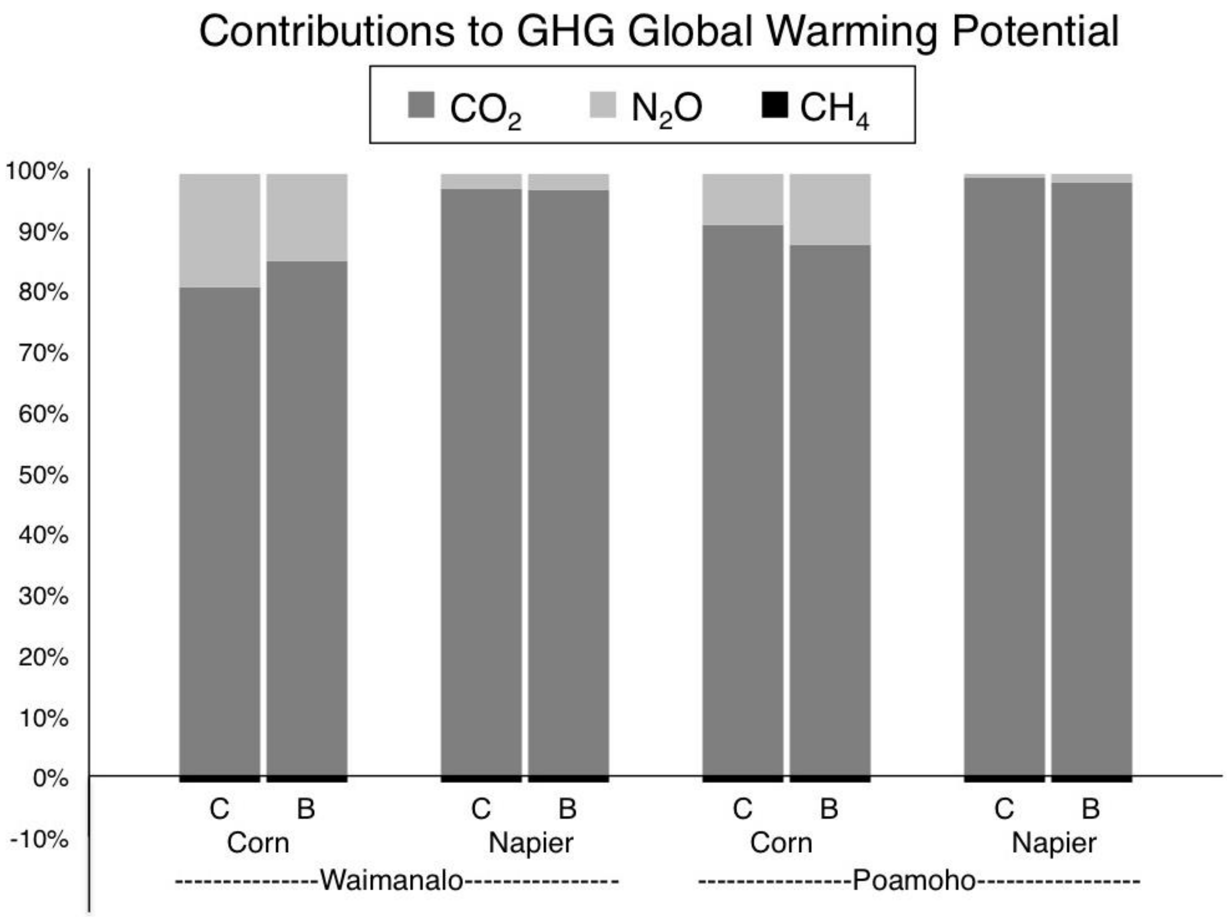

Figure 2.9. Contribution of the three principal GHGs to total GHG-GWP, expressed as a percentage, in each site, crop, and treatment (Control=C, Biochar=B).

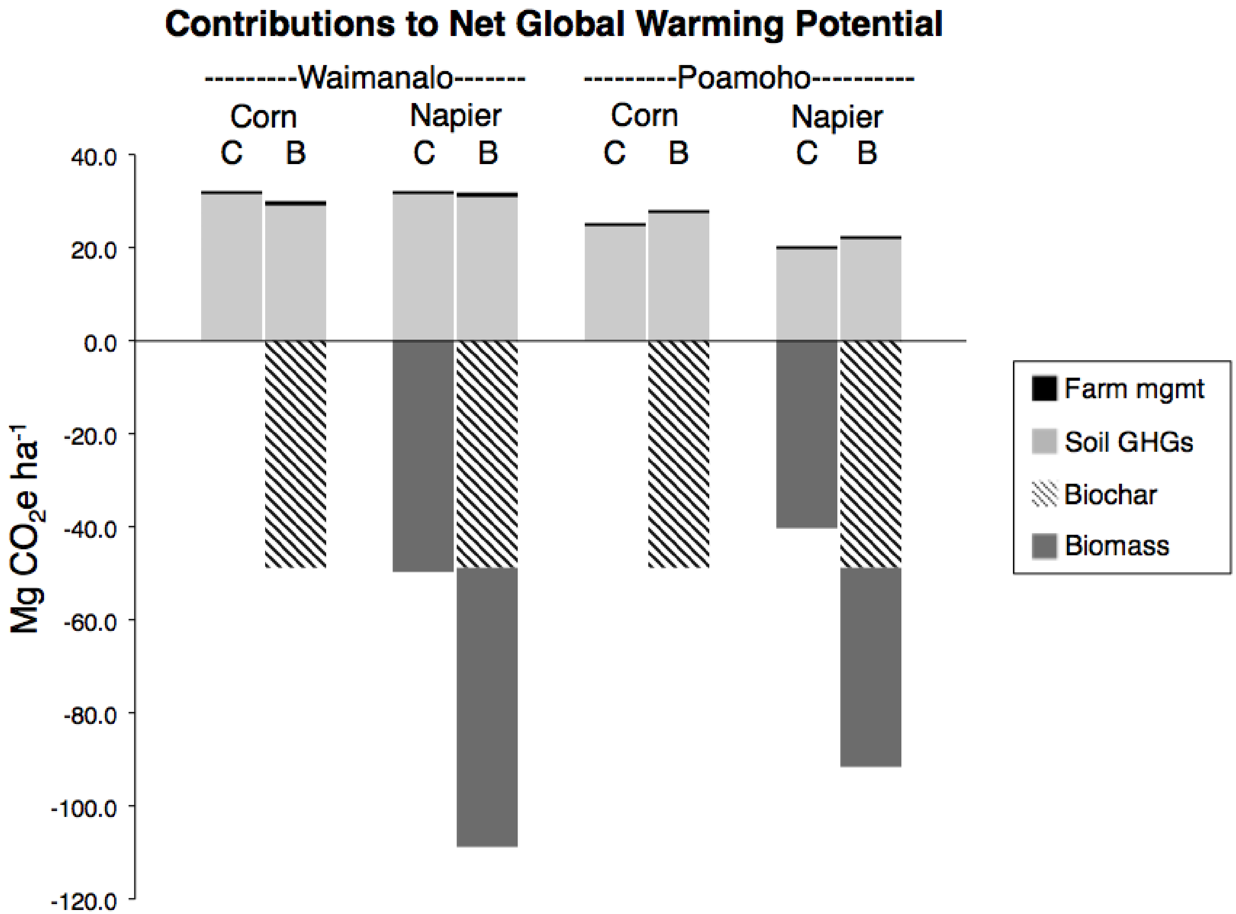

Figure 2.10. Contributions of four factors to year one net GWP in each site, crop, and treatment (Control=C, Biochar=B).

When all factors contributing to net GWP are combined, assuming a one-time addition of biochar to soil in the first year of production in the biochar treatment, napier grass crops with biochar amendment possessed the most strongly negative net GWP of all systems (Figure 2.11). Sweet corn crops managed without biochar amendment was the only case in which net GWP was positive, since either biochar amendment alone or napier grass biofuel potential alone was more than enough to offset GHG-related positive GWP.

In year two, and every year thereafter, napier grass possessed a great advantage in terms of net GWP over sweet corn due to the nature of the biofuel potential of its biomass; napier grass net GWP at both sites and both treatments was negative while that of sweet corn was positive, with an average difference of about 50 Mg CO_2e/ha between crops (Figure 2.12). In these successive years, differences in net GWP between biochar and control treatments were due to GHG emissions and napier biomass alone. In the case of napier grass, biochar treatment resulted in a reduction of net GWP at Waimanalo due to notable increases in crop yields alone; at Poamoho, the slight yield gain due to biochar was almost entirely counteracted by increased GHG emissions, resulting in little difference in net GWP between treatments. In regards to sweet corn, treatment dissimilarities in post-first year net GWP were parallel to trends in GHG emissions; Waimanalo saw a slight reduction owed mostly to moderate reduction of emissions of N_2O. Contrastingly, Poamoho biochar treatment resulted in the opposite outcome—a slight increase in net GWP owed to modest increases in emissions of N_2O and CO_2.

These results support the hypothesis that biochar amendment would mitigate GWP in both crops and both soils; however, this is true only on a short time scale in the case of Poamoho crops. Because GHG emissions from the soil were slightly increased, the GWP reduction achieved through biochar amendment is offset after 17 years for sweet corn and 23 years for napier grass production. In conclusion, biochar amendment did result in a large one-time addition of pyrolyzed C to the soil. At Waimanalo, GHG emissions did not increase; at Poamoho, GHG emissions increased enough to offset biochar C addition only in the long term.

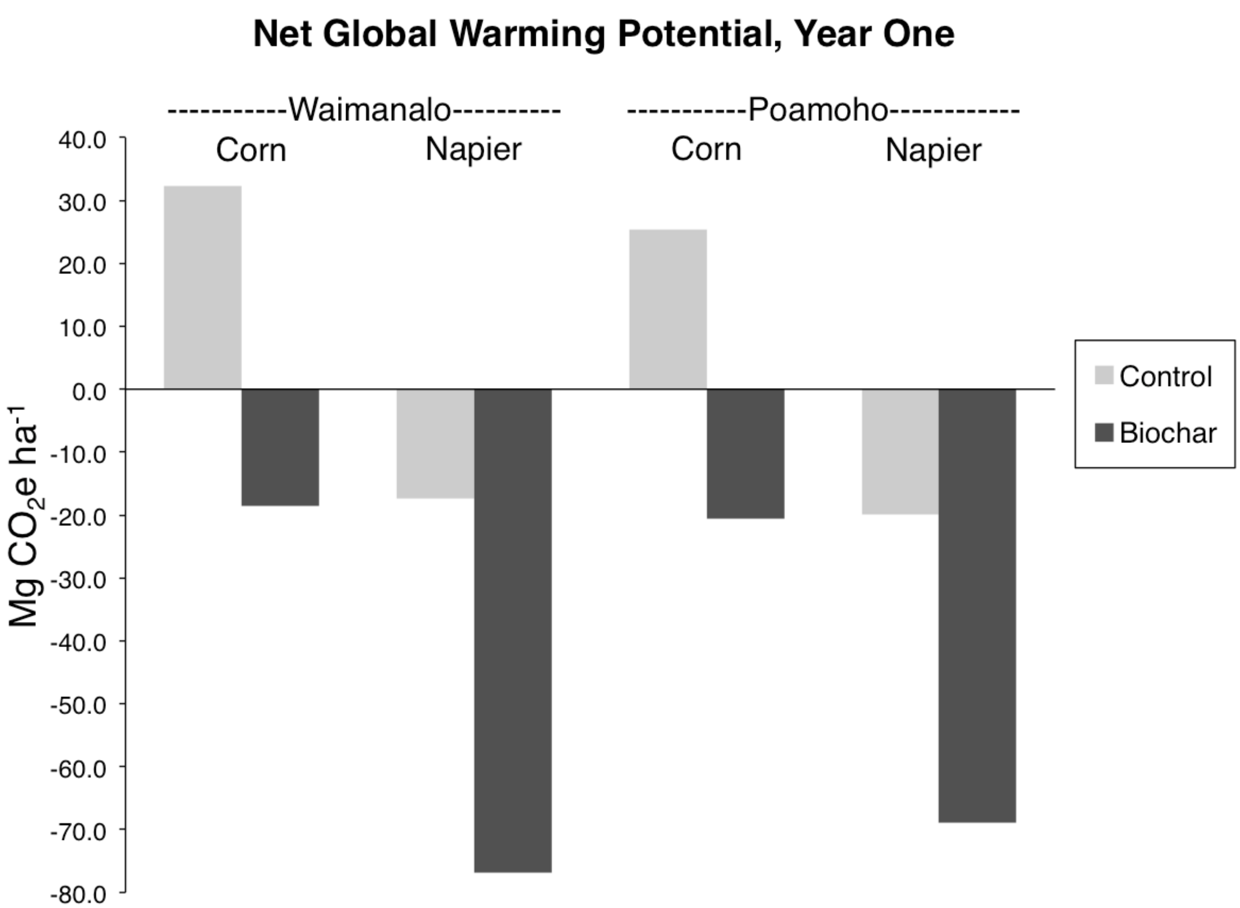

Figure 2.11. Year one net GWP for each site, crop, and treatment. In year one, biochar amendment contributes a large, one-time amount of negative GWP to biochar treatment systems in addition to differences in GHG emissions and crop yields between treatments.

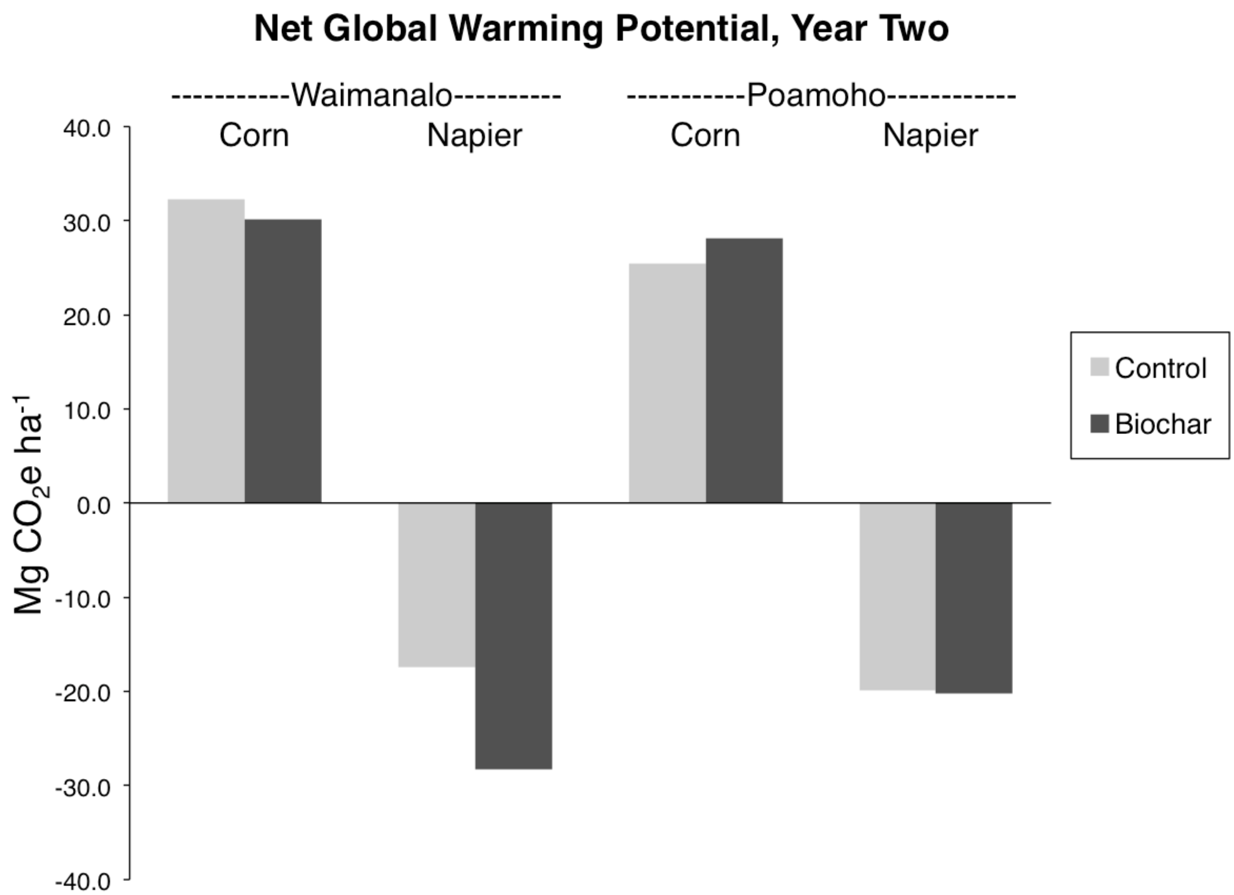

Figure 2.12. Year two net GWP for each site, crop, and treatment. In year two, and every year thereafter, differences between control and biochar treatments are owed to GHG emissions and crop yields alone.

Chapter 3: Primary Economic Analysis

Introduction

Evaluating the sustainability of a system using a triple bottom line approach is an effective method for assessing suitability of agricultural practices and management options (Robinson et al., 2012). Full-cost BCA can be used to quantitatively assess the sustainability of an agronomic system by incorporating traditional farm costs and benefits together with the economic value of social and environmental externalities (Lave, 1996; Davies, 2014). Using BCA in this way to value GWP in the same basic economic terms as agronomic inputs and crop yields could create a highly useful indicator of sustainability of farm management options, such as biochar amendment. In regards to the sustainability of biochar amendment, combining social and environmental costs of GWP with traditional economic costs and benefits is a novel method of evaluation that has not been attempted before. This approach was used to study the sustainability of biochar use in Hawaiian agriculture. This chapter presents the primary analysis used for this triple bottom line assessment, using conditions observed in field trials.

Objectives & hypotheses

The objective of this chapter was to assess the sustainability of biochar amendment via valuation of agronomic inputs, yields, environmental and social externalities of GWP, and incorporation of all three measures into BCA over a 25-year time frame. It was hypothesized that biochar amendment in both crops would result in enhanced sustainability through increased crop yields and mitigated GWP at Waimanalo, and through increased crop yields alone at Poamoho. GWP was valued using a CO_2e price scenario. Production inputs were quantified and valued using market prices. Crop yields were measured at each harvest in field trials and valued using market prices. Overall BCA results were compared in terms of NPV as an indicator of system sustainability.

Methods

Input quantification and valuation

Input data was monitored and estimated based on actual quantities of materials and time used in field trials. All inputs, with exception of labor and machinery, were scaled up from field trails to a per-ha basis using a conversion factor of 107639 square feet per ha. To account for differences in efficiency, inputs of labor and machinery were adjusted from field trials to commercial scale by estimating actual labor and machinery demands for full production-scale cultivation based on standard Hawaiian practices for crop production. Total annual hours of input per ha were estimated to be, for napier grass, 56.8 man-hours of labor and 27.2 hours of machinery use and, for sweet corn, 170.5 man-hours of labor and 81.5 hours of machinery use. Diesel fuel consumption by farm machinery was estimated based on known rated take-off horsepower and a conversion factor of 0.167 liters per hour per horsepower (Grisso et al., 2010). Prices used for valuing agronomic inputs (Table 3.1) were adjusted from U.S. national average data to be representative of the Hawaiian economy based on state and national consumer price index (CPI) data (US BLS, 2014). Biochar cost was based on the market value of the actual biochar used in field trials according to the commercial producer from which it was obtained via benefaction. Total biochar investment cost included purchase, shipping, and application in the field.

Item	Price	Unit	Source
Lime	$0.07	/kg	USDA NASS, 2014
Diesel fuel	$1.02	/l	USDA NASS, 2014
Labor	$13.31	/hr	USDA NASS, 2014
Potash	$0.73	/kg	USDA NASS, 2014
FBM	$0.46	/kg	Island Commodities Inc., 2014
Biochar	$2.71	/kg	Diacarbon, Inc., 2014
Biochar shipping	$3.06	/kg	Actual cost in 2013
Irrigation water	$0.45	/1000 l	Honolulu Board of Water Supply, 2014
Sweet corn seed	$15.43	/kg	UH Seed Lab, 2014
Napier grass cuttings	$90.67	/ha	Kinoshita & Zhou, 1999 ($25/acre)
Cowpea seed	$2.16	/kg	Survey of local market prices
Lorox 50W	$57.56	/kg	Survey of local market prices
Sevin 4F	$14.37	/l	Survey of local market prices

Table 3.1. Prices used for economic valuation of agronomic inputs, presented in 2014 dollars.

Crop yield measurement and valuation

Crop yields were measured at each harvest by weighing of napier grass biomass and fresh sweet corn ears. In field trial plots, the outer rows were harvested and discarded as buffer rows, while the inner rows were harvested and weighed, serving as the yield measurement. Regarding sweet corn, ears were separated based on size and quality into two categories, marketable and nonmarketable. Hawai'i-specific 2006 market prices of sweet corn and napier grass were inflated to 2014 prices using CPI data, while napier grass price was obtained from the Kauai Island Utility Cooperative (Table 3.2) (US BLS, 2014). Sweet corn fresh market price was valued at $1789.91 per Mg, while napier grass was valued at $108.48 per Mg (dry weight) for biofuel production. These prices were used to value crop yields measured from harvests.

Crop	2014 Price ($/Mg)	Source
Sweet Corn	$1,789.91	USDA NASS & HI Ag Stats Service
Napier Grass	$108.48	Kauai Island Utility Cooperative

Table 3.2. Hawaiian market prices for crop yields from sweet corn and napier grass, adjusted to 2014 dollars from 2006 data.

Valuation of GWP

The economic value of GWP was calculated using the price of $40.60 per metric ton of CO_2e (tCO_2e); this figure was selected based on the social cost of carbon (SCC) estimated by the US EPA, which the agency uses to assess the climate costs and benefits of rulemakings (Interagency Working Group on Social Cost of Carbon, 2010). This price attempts to reflect the social and environmental cost of climate change resulting from a given additional amount of CO_2 added to (or removed from) the Earth's atmosphere. Additionally, the price of \$40.60/tCO_2e is representative of average prices across several national, regional, and local attempts at CO_2 valuation. This price was applied to the net GWP calculated in the previous chapter to value GWP in the same terms as other economic inputs and outputs, capturing the full cost to society of perturbing or mitigating climate change.

Benefit-cost analysis

Economic analysis included full-cost accounting BCA to evaluate the sustainability of each management system and for relative comparison between managements for a period of 25 years using an inflation rate of 3.24% based on historical rates (US BLS, 2014). In the BCA, the costs and benefits associated with biochar amendment were considered along with all other agronomic factors in the cropping system using the full cost accounting approach to include valuation of social and environmental costs of GWP. Components of production inputs include irrigation water, fertilizer, and biochar, and cost of labor and machinery in land preparation, planting, and harvesting. The benefits generated by the system were market valuation of crop yields and, in some cases, GWP mitigation. Costs and benefits over the 25-year BCA period were discounted to 2014 dollars to calculate the NPV (Boardman et al., 2001) of each management option using a discount rate of 4.73%, as determined by the average historical primary discount rate of the last 25 years (Federal Reserve, 2014).

The payback period, or the length of time required for an investment to pay for itself, was calculated for the implementation of biochar amendment in cases where the NPV of biochar amendment was positive and greater than that of the control. Joint consideration of the payback period and of NPV is desirable because the payback period gives insight into the temporal nature of biochar investment recovery in the form of potential yield improvement and GWP mitigation, while NPV gives insight into the relative balance of costs and returns between management systems.

Results & discussion

Cost of production

Total production costs for sweet corn were between about \$5,000 and \$7,000 higher than that of napier grass (Tables 2.3 & 2.4). For both crops, production costs were higher at Waimanalo than at Poamoho—about \$3,000 higher for sweet corn and \$2,000 higher for napier grass. Across both crops and both sites, considerable differences in the first year's production costs were present between biochar and control treatments. The biochar treatment was an order of magnitude more expensive than the control in year one. Biochar treatment production costs were high in year one with respect to the control treatment, but were identical in year two.

The observed differences between total cost of production for sweet corn and napier grass were due to differences in crop and soil management such as tillage, planting, cover cropping, pesticide application, and irrigation. Labor and machinery use associated with tillage and planting were the two largest factors that affected differences in input cost due to the no-till, ratoon harvest management of perennial napier grass in contrast with the frequent tillage and repeated planting necessary for cultivation of the corn crop; plus, the inclusion of a cowpea cover crop added additional tillage and planting demands into the sweet corn cropping system.

For both crops, production costs were higher at Waimanalo than at Poamoho; this is despite the fact that the Oxisol at Poamoho required liming while the Mollisol at Waimanalo did not, and sweet corn at Poamoho required pesticide application while that of Waimanalo did not. This difference between sites was exclusively due to differences in irrigation. Compared to Poamoho, the amount of water needed for crop irrigation at Waimanalo was 30% larger in the napier grass crop and 24% larger for sweet corn. Although average annual rainfall was higher at the Waimanalo field site versus Poamoho, average air temperature and incoming solar radiation were also higher, resulting in a larger amount of potential evapotranspiration present at Waimanalo than Poamoho (Giambelluca et al., 2014).

In all crops and sites, considerable differences in input costs during the first year of production occurred between biochar and control treatments. Because control and biochar treatments were managed identically with the exception of addition of biochar at the beginning of cultivation, the difference between treatment input costs mirrored the cost of procurement of biochar, plus slight differences in labor and machinery use for incorporation in the field. Sourcing of biochar from a commercial, off-island producer required large monetary investment necessary for purchase and shipment of the product, resulting in a ten-fold increase in cost of production over the control treatment. After year one, cost of production was identical between treatments since biochar amendment occurred only in the first year of production.

		Total Cost ($/ha)	
Site	Treatment	Year 1	Year 2
Poamoho	Biochar	$107,296.18	$13,258.57
	Control	$13,258.57	$13,258.57
Waimanalo	Biochar	$110,431.16	$16,393.55
	Control	$16,393.55	$16,393.55

Table 3.3. Sweet corn annual cost of production based on field trial inputs adjusted to commercial-scale production.

		Total Cost ($/ha)	
Site	Treatment	Year 1	Year 2
Poamoho	Biochar	$102,596.72	$7,224.40
	Control	$8,559.10	$7,224.40
Waimanalo	Biochar	$104,656.70	$9,374.30
	Control	$10,619.08	$9,374.30

Table 3.4. Napier grass annual cost of production based on field trial inputs adjusted to commercial-scale production.

Crop yields and valuation

Sweet corn yields from field trials were highly variable across the four harvests (Table 3.5). Conditions of near crop failure occurred on separate occasions at both sites, as well as instances of abnormally high yields relative to expected yields of sweet corn in Hawaiʻi of about 6.0 Mg/ha (USDA & HI Ag Stats Service, 2010). Abnormally low yields of sweet corn occurred at the last harvest at Poamoho (2.92–3.33 Mg/ha) and at the second harvest at Waimanalo (2.25–2.54 Mg/ha). In contrast to these incidences of poor yields, exceptionally high crop yields were also observed at the second and third harvests at Poamoho (~14–17 Mg/ha) and the first harvest at Waimanalo (~11-13 Mg/ha).

Comparatively, napier grass crop yields were more predictable than sweet corn, with exception of the last of the four harvests (Table 3.6). Napier grass yields were lower than expected at the last harvest in December 2015 at both Poamoho and Waimanalo. Crop yields were only 25–32 Mg/ha compared to 50–71 Mg/ha at the previous harvest in June 2015. Napier grass yields tended to increase with sequential harvests following initial planting of cuttings. Poamoho yields increased steadily over the first three harvests, while Waimanalo yields increased dramatically at the second harvest and then leveled off, dropping slightly at the June 2015 harvest. Overall, yields of napier grass were consistently higher at Waimanalo than Poamoho in both treatments at every harvest.

Biochar treatment tended to have lower yields than the control treatment in sweet corn at both field sites. In contrast, napier grass biochar treatment generally resulted in higher yields than the control at both sites. On average, sweet corn yields with biochar treatment were about 5% less than that of the control treatment; in the case of napier grass, yields were about 14% greater with biochar treatment. Especially in napier grass grown at Waimanalo, biochar treatment crops consistently outgrew control treatment crops—an average yield increase of around 21%. These results are somewhat contrary to what was found in a meta-analysis of 84 studies of crop yield response to biochar amendment, where low soil CEC and C content were shown to be strong predictors of positive yield responses (Crane-Droesch et al., 2013). It has also been demonstrated that the beneficial components of biochar to soil fertility in Oxisols tend to manifest over time, and that positive effects may not be observed in the first crops immediately following amendment (Major et al., 2010). In this respect, a possible limitation of this experiment is that the yield effects of biochar were observed in only the first two years of production; However, the unique growing season in Hawaiʻi allowed for two harvests per year and yield effects were generally consistent across all four harvests of each crop.

In the case of napier grass, poor yields at the last harvest in December 2015 were due to weather-related factors such as strong winds and heavy rainfall events as a result of tropical storms passing over the island, which affected both field sites. These factors resulted in crop yields of around only 50% of expected values, mainly due to lodging—plants falling over from their normal vertical growth into a semi-horizontal orientation—resulting in physical damage to shoots and stems, with diminished photosynthetic potential thereafter.

Poor yields of sweet corn, on the other hand, were due to both weather-related stressors and pest invasion issues. All corn crops were heavily afflicted by earworm, even when yields were normal or above average. At Waimanalo, the poor yield from the October 2014 harvest was due to concurrent issues of the leafhopper insect and disease, likely a combination of corn smut and rust. Smut continued to plague the crop at Waimanalo during both crops in 2015. At Poamoho, the last harvest of sweet corn in October 2015 had especially poor yields; this was due perhaps entirely to lodging that occurred as a result of heavy rainfall and high wind. Higher than expected yields of sweet corn were harvested during the second and third harvests at Poamoho, amounting to as high as 17.44 Mg/ha, a quantity strikingly higher than the average yields for the crop in Hawai'i of about 6 Mg/ha. At Waimanalo, yields were more typical of the crop's performance in Hawai'i. One possible explanation for these incidences of exceptionally large crop yields could be that management practices used in the field trials were different than that of what is used in typical production of the crop across the state. For example, large amounts of N-fertilization with FBM and more-than-adequate water supply with drip irrigation used in the field trials may have been far superior to management practices typically employed in contemporary sweet corn production in Hawai'i.

Revenues hypothetically generated from crop yields were directly proportional to crop yields. Overall, sweet corn tended to be a more valuable crop than napier grass in terms of annual revenues due to the huge difference in market price for the crop products (Figures 2.5 & 2.6). Although the biomass harvested was far greater in napier grass than sweet corn, the sweet corn fresh market ears were a more valuable commodity in terms of price. Sweet corn grown at the Poamoho field site generated greater revenues than Waimanalo due to the two instances of exceptionally large yields at Poamoho. Napier grass, on the other hand, generated more revenue at Waimanalo than Poamoho due to consistently higher yields of crop biomass. In the case of sweet corn, biochar treatment crop revenues were consistently less than that of the control treatment across both sites and years. Napier grass, however, generally exhibited greater revenues from biochar treatment crops than control.

		Marketable Ear Yield (Mg/ha)				Annual Revenue ($/ha)	
Site	Treatment	Jun-14	Oct-14	Jun-15	Oct-15	Year 1	Year 2
Poamoho	Biochar	6.75	13.88	16.34	2.92	$36,917.94	$34,470.73
	Control	6.61	15.36	17.44	3.33	$39,317.12	$37,168.44
Waimanalo	Biochar	10.93	2.54	4.95	5.48	$24,100.15	$18,669.86
	Control	12.93	2.25	5.29	5.91	$27,166.12	$20,040.13

Table 3.5. Sweet corn yields from field trials on O'ahu. Yield includes only fresh ears that were categorized as marketable. Instances of both atypically high and low crop yields occurred at both sites.

		Dry Weight Yield (Mg/ha)				Annual Revenue ($/ha)	
Site	Treatment	Jun-14	Dec-14	Jun-15	Dec-15	Year 1	Year 2
Poamoho	Biochar	36.35	40.77	49.94	25.47	$8,365.65	$8,180.18
	Control	33.07	34.37	53.40	25.24	$7,315.55	$8,530.40
Waimanalo	Biochar	44.08	73.43	70.89	32.02	$12,746.76	$11,163.06
	Control	36.70	61.08	58.83	25.67	$10,606.70	$9,166.96

Table 3.6. Napier grass yields from field trials on Oʻahu. Yields from the last harvest were atypically low due to abnormal weather conditions.

Valuation of GWP

In the case of both field sites and both treatments, the economic value of net GWP was considerably higher in napier grass systems than sweet corn systems in the first year of production (+$1,800–$2,200/ha/yr) (Table 3.7). In year two, GWP values of all sites and treatments were slightly higher in napier grass than sweet corn, except for sweet corn at Poamoho, in which case it was slightly more negative. Year one GWP value was slightly higher in both treatments and both crops at Poamoho than Waimanalo, with exception of the biochar treatment napier grass, which was slightly lower. In year two, the identical relationship was observed.

During year one, biochar treatment resulted in a markedly more positive economic value of GWP compared to the control in all systems. In cases of negative value of GWP in control sweet corn during the first year of production, biochar treatment resulted in a positive value. In regards to napier grass, year one GWP value in biochar treatment was considerably higher than the already-positive GWP value of the control, a difference of about $2,000/ha/yr. In year two, however, the effect of biochar treatment on GWP value was mixed. In napier grass, year two GWP value was higher by about $440/ha/yr at Waimanalo, but only marginally higher with biochar treatment than the control at Poamoho. In contrast, sweet corn GWP value in year two was slightly less negative with biochar treatment at Waimanalo and slightly more negative at Poamoho. In year two, and all sequential years of production, the value of GWP was identical as that of year one for control treatments while it was considerably less for biochar treatments.

The marked increase in GWP value in year one with biochar treatment was due to the large benefit of biochar C being added into the soil C pool. Additionally, in the case of napier grass, some of the observed difference was due to increased crop yields with biochar treatment, which translates into an increased biofuel potential of the crop harvest. The increases in GHG emissions that were observed with biochar treatment had a relatively small impact to net GWP, compared to the benefits of biochar C sequestration. In year two (and all sequential years), however, treatment differences in GHG emissions weighed in more importantly. Because there was no biochar benefit obtained in year two, increased GHG emissions resulted in a decreased GWP value in sweet corn at Poamoho, pushing it even further negative. Napier grass biochar treatment GWP value was still higher in year 2 than the control due to the continued benefits of increased crop yields.

		Value of net GWP, \$/ha/yr		
Site	Crop	Control	Biochar, yr 1	Biochar, yr 2
Waimanalo	Sweet Corn	\$(1,074.68)	\$930.83	\$(1,046.25)
	Napier Grass	\$746.12	\$3,163.92	\$1,186.83
Poamoho	Sweet Corn	\$(947.40)	\$960.89	\$(1,016.20)
	Napier Grass	\$818.60	\$2,823.02	\$845.93

Table 3.7. Annual economic value of net GWP per hectare based on US EPA SCC, \$40.60/Mg CO_2e. Parentheses denote a negative value. Control GWP value was unchanging over time, while biochar GWP value was different in the first year of production from the second and all following years.

Benefit-cost analysis
The biochar treatment in all systems consistently resulted in a markedly lower NPV than the control treatment (Figures 3.1 & 3.2). The NPV disparity between biochar and control treatments was as high as 159% in Poamoho napier grass and 142% in Waimanalo sweet corn, wherein both NPVs went from positive with control treatment to negative with biochar. In Poamoho sweet corn, NPV was 23% lower in biochar treatment than control; in Waimanalo napier grass it was 61% lower.

The consistently lower NPV induced by biochar amendment was largely due to the high investment cost of biochar procurement in the first year of production. In the case of napier grass, this was the main factor affecting BCA performance; at Waimanalo, it far outweighed any benefits obtained from increased crop yields in terms of both crop revenue and crop biofuel potential. At Poamoho, the BCA performance of biochar treatment was even worse because, while yields were slightly increased during year one, a marginal reduction in crop yields occurred in year two. Coupled with high investment cost, these factors resulted in infeasibility of biochar amendment in the napier grass crop with the considered sourcing of biochar and the yields obtained from field trials.

While Waimanalo sweet corn had a small decrease in GHG emissions with biochar treatment—mainly N_2O—the investment cost of biochar far outweighed GWP benefits from GHG emissions and biochar C combined. Additionally, biochar treatment resulted in slightly decreased yield revenues from sweet corn at both sites. Some of the difference between Poamoho and Waimanalo BCA performance is due to moderately lower cost of production at the Poamoho field site, mainly through decreased irrigation demands; also, sweet corn crop revenues were higher at Poamoho in both year one and sequential years of production. These factors combined resulted in differences between field sites.

In conclusion, biochar amendment did result in some benefits—napier grass crop yields were increased at Waimanalo and net GWP was mitigated in all systems except Poamoho sweet corn. However, the hypothesis that enhanced sustainability would result from biochar amendment in both crops was not supported by the results of the primary BCA. The investment cost of purchasing and shipping the biochar product was too high to allow for any benefits of amendment to be realized. If biochar investment costs could be reduced to a more modest amount, it is possible that increased crop yield revenues and increased GWP value could outweigh the upfront cost within the 25-year BCA period for some crops. Further, if the value of GWP was enhanced due to a different market price of CO_2e, or if crop yield revenues were higher, it is possible that the large investment cost necessary for sourcing biochar could eventually become worthwhile in the long term.

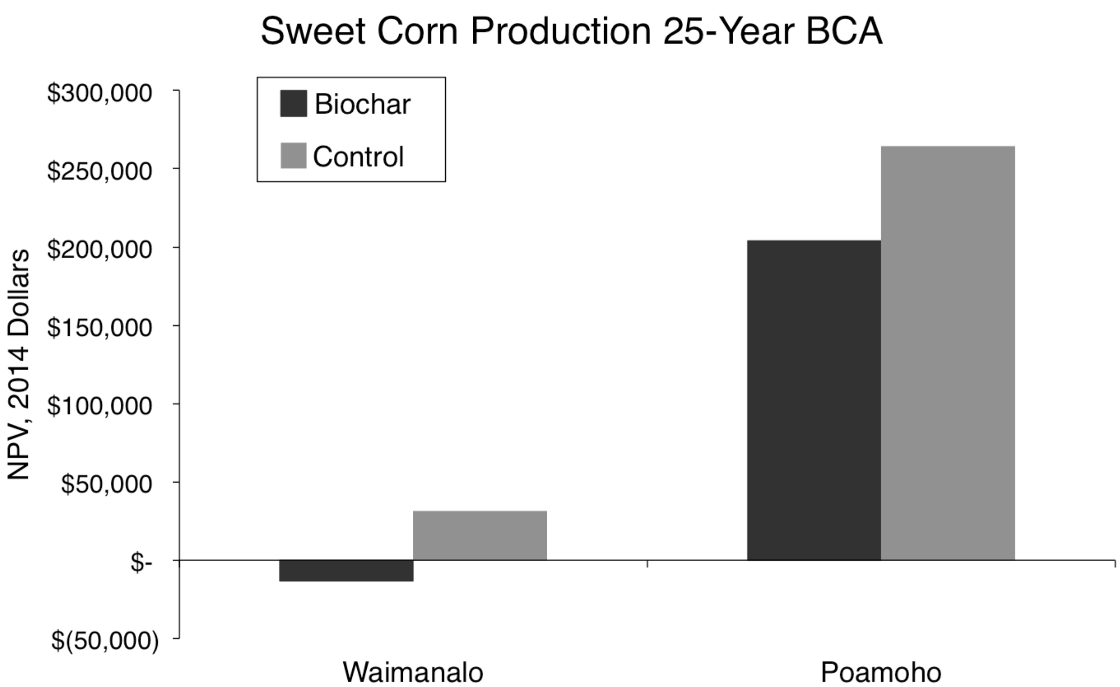

Figure 3.1. 25-year BCA of sweet corn production expressed as 2014 NPV, based on field trial yields and actual market price of biochar.

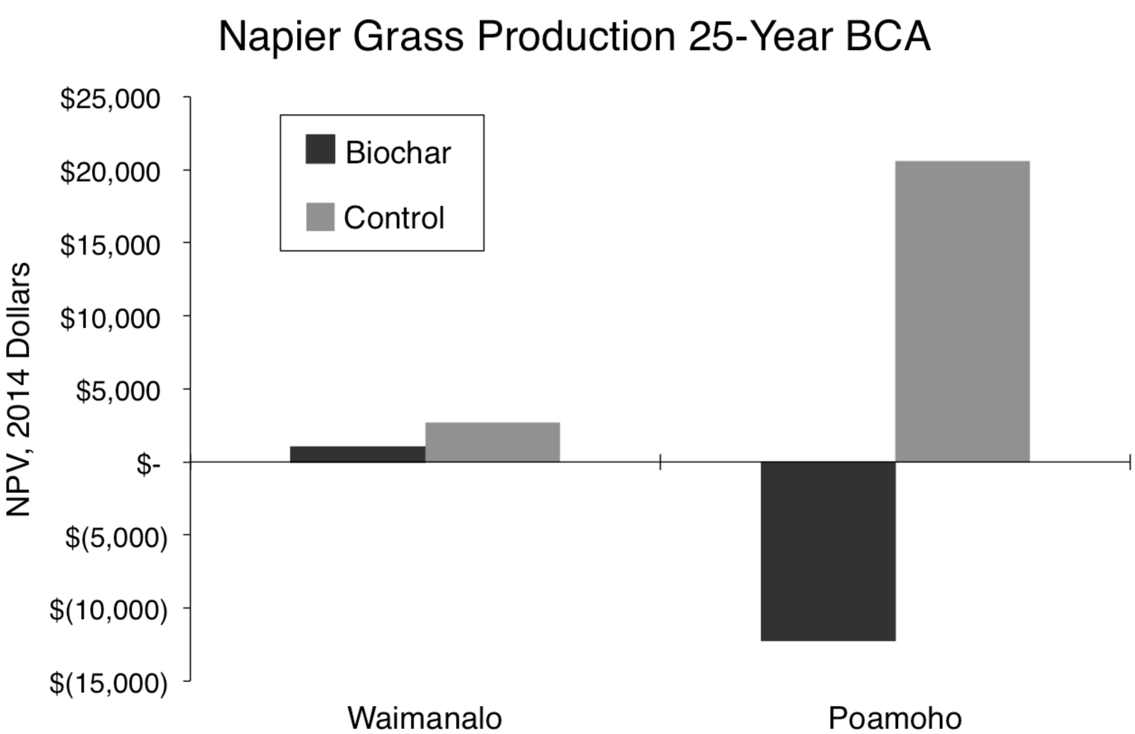

Figure 3.2. 25-year BCA of napier grass production expressed as 2014 NPV, based on field trial yields and actual market price of biochar.

Chapter 4. Scenario Testing and Sensitivity Analysis

Introduction

The previous chapter's primary analysis considered biochar amendment in Hawaiian agriculture under a basic set of circumstances that were largely bound to the state of field trial experiments. Under these basic conditions considered in the previous chapter's analysis, the outlook for biochar amendment as a farm management practice appears unsustainable, if not entirely infeasible. However, because the analysis thus far has been strictly limited to one rigid set of circumstances, it is necessary to explore a wider range of social, economic, and environmental variables—both actual and hypothetical—in order to more fully assess the option of biochar amendment. The purpose of this chapter is to explore a variety of scenarios in which the prospect of biochar amendment may vary according to circumstance, and if so, the relative importance of a set of relevant variables that partially determine system sustainability.

Three variables were identified as high priority for consideration: 1) crop yield revenue, 2) biochar investment cost, and 3) CO_2e prices used for GWP valuation. Crop yields from field trials were, in some cases, not representative of expected yields for typical crop production in the region; thus, the primary analysis may be inaccurately representing revenues generated from crop yields. Similarly, the investment cost of biochar was based on the way in which biochar was obtained for field experiments, which was a particularly expensive method of procurement. A variety of ways in which a farmer might source biochar exist, and therefore the primary analysis needs expanding to include a range of methods. Lastly, the price used for valuation of GWP was limited to just one scenario of CO_2e valuation; in reality, there have been many attempts at putting a dollar value on the costs of fueling climate change, and, thus, a wide range of possible prices exist, both present and future.

Objectives & hypotheses

For the reasons stated above, a set of adjusted crop yields were developed based on average crop yields for the State of Hawai'i, average weather conditions, and treatment differences observed in the field. Next, a contrasting scenario of biochar procurement was developed as an alternative to the method used in the primary analysis. Lastly, three scenarios of CO_2e prices were selected for valuation of GWP, ranging between extreme lower and upper ends of a range of estimated costs of fueling climate change. It was hypothesized that the investment cost of acquiring biochar would be the most important factor in determining the sustainability of the biochar system as measured by NPV. Alternative scenarios of key variables were developed and tested in BCA. A sensitivity analysis was used to compare relative weights of variables in affecting NPV.

Methods

Crop yield adjustment

Due to some harvests' crop yields representing conditions of near crop failure, as well as instances of exceptionally high yields, an alternative scenario of adjusted yields was developed for comparison with field trial yields. Adjusted crop yields were then used in economic valuation and included in BCA. Due to the high degree of variation in sweet corn crop yields across the four harvests, including both abnormally high and low yields, adjusted crop yields were developed based on the average statewide yield of sweet corn of about 6 Mg/ha (Table 3.5). In the adjustment, this average value was used for control treatment yields while biochar treatment yields were based on the same value adjusted proportionally using actual field trial treatment dissimilarities in yield. In the case of napier grass, only the last harvest's yields were adjusted due to their atypically small nature; the control treatment's yields were simply replicated from the previous harvest (June 2015) while that of biochar was calculated relative to control using real field trial treatment differences (Table 3.6). The resulting adjusted yields in both crops were used as a more appropriate proxy for expected average crop yields for economic valuation and inclusion in BCA.

Biochar scenarios

For purposes of biochar investment cost in the economic assessment, procurement of the biochar product was considered under two contrasting scenarios: 1) Commercial: Purchase of biochar from a commercial-scale producer in North America, including any associated shipping costs; and 2) Do it yourself (DIY): Small-scale on-farm production of biochar utilizing a readily available local biomass as feedstock and simple, homemade equipment for pyrolysis based on International Biochar Initiative (IBI) open source technology. Both scenarios included the same biochar application rate of 1% by mass, and a one-time application at year one prior to planting. Total biochar investment cost included cost of biochar procurement (as defined by the two scenarios) and the costs of applying biochar in the field. The price of biochar in the commercial scenario was determined to be $5.78/kg based on the market value of biochar used in field trials ($2.71/kg) combined with actual shipping costs ($3.06/kg) paid for shipping of 816.5 kg of biochar from mainland North America to Oʻahu, Hawaiʻi in 2013. The price of biochar in the DIY scenario was determined to be $0.60/kg by estimating costs of material and labor for constructing homemade pyrolysis units and producing biochar from a readily available, local feedstock. Construction of pyrolysis units was based on IBI open source technology for small-scale biochar production.

Scenario	Price ($/kg)	Source
Commercial	$5.78	Actual market price, 2013
DIY	$0.60	Estimated, IBI open source technology

Table 4.1. Prices used in evaluating two scenarios of sourcing biochar product.

Price of CO_2e

Scenarios were tested to explore the feasibility of each management system across three market prices of CO_2e based on projected upper and lower values of 2014 prices of CO_2. The three prices used to value GWP ranged from $12.97 to $105.03/t$CO_2e$ based on several scenarios of social and environmental costs of GHG emissions (Table 4.2). The low scenario value of \$12.97/tCO_2e was selected based on the California cap and trade market's baseline 2015 price adjusted to 2014 dollars. The medium value of \$40.60/tCO_2e—the same as that which was used in the primary BCA—was selected based on the SCC used by the US EPA to estimate the climate costs and benefits of rulemakings (Interagency Working Group on Social Cost of Carbon, 2010). The upper value of \$105.03/tCO_2e was selected based on Dietz and Stern's 2014 modeling efforts that suggest it as the high end of a range of optimum prices to capture the true social and environmental cost of emissions, and could avoid the most disastrous effects of increasing global temperature if implemented in worldwide C markets by 2025. The medium C pricing scenario was selected as the preferred scenario for inclusion in the final BCA.

Scenario	Price (\$/tCO_2e)	Source
Low	\$12.97	California Cap and Trade, 2015
Medium (preferred)	\$40.60	US EPA SCC, 2015
High	\$105.03	Dietz and Stern, 2014

Table 4.2. Pricing scenarios for GWP economic valuation, presented in 2014 dollars. The medium scenario was used as the preferred price for use in the original BCA.

BCA and sensitivity analysis

The three variables considered under alternate scenarios were included in BCA for comparison with primary analysis. With respect to each individual scenario, all other components of the BCA were unchanged. The same methods of BCA were used as in Chapter 3, which included evaluation in terms of NPV. Then, to assess the relative importance of each variable, a basic sensitivity analysis was performed using BCA results. Sensitivity analysis consisted of a simple correlation of each variable's scenarios with their respective NPV by a creating a line to quantify the slope; the relative sensitivity of NPV to each variable, and, thus, the relative power of each variable in determining the outcome of biochar amendment sustainability, was assessed (Paruolo et al., 2013). For each variable, the line slopes for each of the four crop and soil combinations were averaged. The absolute value of the average slope was used as a coefficient (ß) for quantification of sensitivity. Sensitivity analysis assessed the relative importance of crop yield, biochar investment cost, and CO_2e price in determining the NPV of the biochar amendment option in both crops at both sites.

Results and discussion

Adjusted crop yields

Using adjusted crop yields, revenues generated from sweet corn crops were higher than that of napier grass (Tables 4.3 & 4.4). Although napier grass harvestable biomass was much greater than that of sweet corn ears, the market value of sweet corn was more than 10 times greater than napier grass. The result was a difference of about \$10,000 in average annual revenue between crops. In the case of napier grass, annual revenue was higher at Waimanalo than Poamoho. Sweet corn annual revenue was similar between sites in the case of adjusted yields. Annual revenue from crop yields in the case of sweet corn was marginally smaller with biochar treatment than with the control. Napier grass crop revenue, however, was marginally larger in biochar versus control treatments.

		Marketable Ear Yield (Mg/ha)				Annual Revenue ($/ha)	
Site	Treatment	Jun-14	Oct-14	Jun-15	Oct-15	Year 1	Year 2
Poamoho	Biochar	6.13	5.42	5.62	5.27	$20,673.97	$19,487.78
	Control	6.00	6.00	6.00	6.00	$21,478.90	$21,478.90
Waimanalo	Biochar	5.07	6.77	5.62	5.56	$21,188.55	$20,015.94
	Control	6.00	6.00	6.00	6.00	$21,478.90	$21,478.90

Table 4.3. Sweet corn adjusted yields and economic valuation. Yield adjustment was based on average statewide sweet corn yields adjusted proportionally to field trial treatment effects.

		Dry Weight Yield (Mg/ha)				Annual Revenue ($/ha)	
Site	Treatment	Jun-14	Dec-14	Jun-15	Dec-15	Year 1	Year 2
Poamoho	Biochar	36.35	40.77	49.94	58.64	$8,365.65	$11,778.04
	Control	33.07	34.37	53.40	53.40	$7,315.55	$11,584.63
Waimanalo	Biochar	44.08	73.43	70.89	71.58	$12,746.76	$15,455.16
	Control	36.70	61.08	58.83	58.83	$10,606.70	$12,763.71

Table 4.4. Napier grass adjusted yields and economic valuation. Adjustment of the fourth harvests' yields was based on previous field trial yields adjusted proportionally to actual field trial treatment differences.

Biochar procurement scenarios

The commercial biochar scenario was an order of magnitude more expensive than the control in year one, while the DIY biochar scenario was only around $10,000 more expensive in year one (Table 4.5 & 4.6). Of the two biochar sourcing scenarios considered, sourcing of biochar from a commercial, off-island producer required large monetary investment necessary for purchase and shipment of the product, resulting in a ten-fold increase in cost of production over the control treatment. In contrast, the DIY biochar scenario, wherein biochar was produced on-farm rather than purchased, had a much smaller investment cost of only about $9,500, comprised mostly of labor costs associated with fabrication of pyrolysis units and the pyrolysis process itself. After year one, cost of production was identical between treatments since biochar amendment occurred only in the first year of production.

Site	Treatment	Total Cost ($/ha) Year 1	Year 2
Poamoho	Biochar, Commercial	$107,296.18	$13,258.57
	Biochar, DIY	$22,806.70	$13,258.57
	Control	$13,258.57	$13,258.57
Waimanalo	Biochar, Commercial	$110,431.16	$16,393.55
	Biochar, DIY	$25,941.68	$16,393.55
	Control	$16,393.55	$16,393.55

Table 4.5. Sweet corn annual cost of production under two different biochar scenarios, based on field trial inputs adjusted to commercial-scale production.

Site	Treatment	Total Cost ($/ha) Year 1	Year 2
Poamoho	Biochar, Commercial	$102,596.72	$7,224.40
	Biochar, DIY	$17,974.13	$7,224.40
	Control	$8,559.10	$7,224.40
Waimanalo	Biochar, Commercial	$104,656.70	$9,374.30
	Biochar, DIY	$20,163.15	$9,374.30
	Control	$10,619.08	$9,374.30

Table 4.6. Napier grass annual cost of production under two different biochar scenarios, based on field trial inputs adjusted to commercial-scale production.

Price of CO_2e

GWP value varied proportionally to the price per Mg CO_2e (Table 4.7). All of the relationships observed between crops, treatments, and sites in the previous chapter's GWP valuation results were identical across all three price scenarios, but with an increased degree of absolute difference in the high scenario, and a smaller degree of absolute difference in the low scenario. Economic value of GWP in all three scenarios was included in BCA for purposes of sensitivity analysis.

			Net Value of GWP, $/ha/yr		
Site	Crop	Treatment	Low	Medium	High
Waimanalo	Sweet Corn	Control	$(343.26)	$(1,074.68)	$(2,780.44)
		Biochar, yr 1	$297.32	$930.83	$2,408.28
		Biochar, yr 2	$(334.18)	$(1,046.25)	$(2,706.89)
	Napier Grass	Control	$238.32	$746.12	$1,930.37
		Biochar, yr 1	$1,010.59	$3,163.92	$8,185.76
		Biochar, yr 2	$379.09	$1,186.83	$3,070.59
Poamoho	Sweet Corn	Control	$(302.61)	$(947.40)	$(2,451.13)
		Biochar, yr 1	$306.92	$960.89	$2,486.03
		Biochar, yr 2	$(324.59)	$(1,016.20)	$(2,629.14)
	Napier Grass	Control	$261.47	$818.60	$2,117.89
		Biochar, yr 1	$901.70	$2,823.02	$7,303.78
		Biochar, yr 2	$270.20	$845.93	$2,188.61

Table 4.7. Net annual economic value of GWP per hectare in three different CO_2e price scenarios, low ($12.97/Mg CO_2e), medium ($40.60/Mg CO_2e), and high ($105.03/Mg CO_2e).

Benefit-cost analysis

In order to observe the effects of adjusted yields and biochar scenarios alone, the BCA results of yield and biochar scenarios are presented here irrespective of CO_2e valuation scenarios, using the original preferred price for GWP valuation. Results of low and high CO_2e valuation scenarios combined with yield and biochar scenarios are presented in Appendix E.

In both crops and both sites, the DIY biochar scenario performed better in the 25-year BCA than the commercial scenario, having higher NPV in all cases (Figures 4.1 & 4.2). In the matter of sweet corn production, control treatment outperformed both commercial and DIY biochar scenarios at both sites. Compared to the NPV of control treatments, that of the DIY scenario was 31% lower at Poamoho and 40% lower at Waimanalo. Commercial biochar NPV performance was more than twice as poor as DIY biochar in comparison to control treatment sweet corn at both sites. Biochar amendment was also found to be economically infeasible in a traditional cost-benefit analysis in North-Western Europe, where investment cost and low expected yield increases were confining factors even under best-case conditions of financing and crop prices (Dickinson et al., 2015).

In the case of napier grass, DIY biochar treatment NPV was significantly higher than control treatment at Waimanalo (+72%), while it was practically equivalent at Poamoho

(+2%). The marked gain in NPV at Waimanalo is attributable to the yield gains accomplished with biochar treatment over control treatment crops. The increased revenue generated through crop yields coupled with increased value of GWP was more than enough to offset the investment cost of biochar production in the case of the DIY scenario; in this case, the payback period for the $9,548.13 investment in biochar amendment was just 3.05 years. In fact, the increased revenue from napier grass crop yields was so significant at Waimanalo that the commercial biochar scenario, even with its large investment cost upfront, resulted in 15% higher NPV over the control treatment. However, in the case of the commercial biochar scenario, the payback period was 30.02 years—a length of time not likely to be attractive to the average Hawaiian farmer with a large investment cost of $94,037.62. The same advantage in terms of NPV of biochar over control treatment was not observed in napier grass at Poamoho because of a less pronounced effect of biochar treatment on crop yields, resulting in little difference in revenue between treatments. Although DIY biochar did marginally outperformed control at Poamoho, the payback period was 32.6 years for an investment cost of $9,548.13.

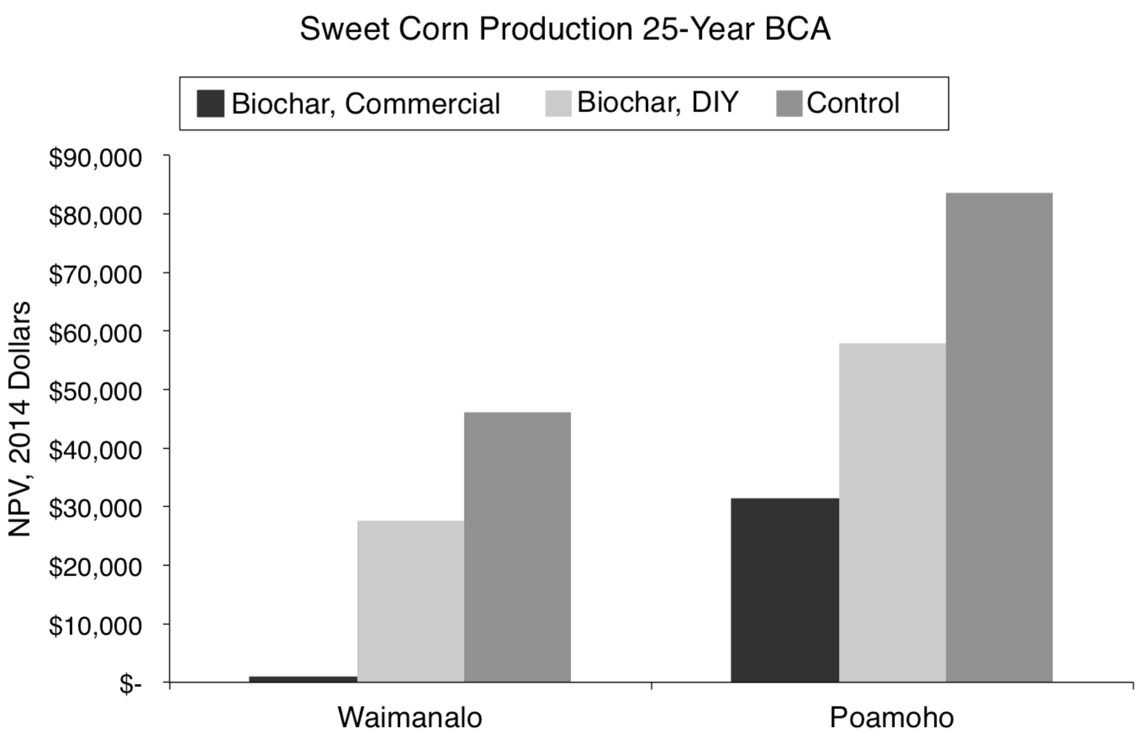

Figure 4.1. 25-year BCA of sweet corn production, expressed as 2014 NPV, using adjusted crop yields and two contrasting biochar procurement scenarios.

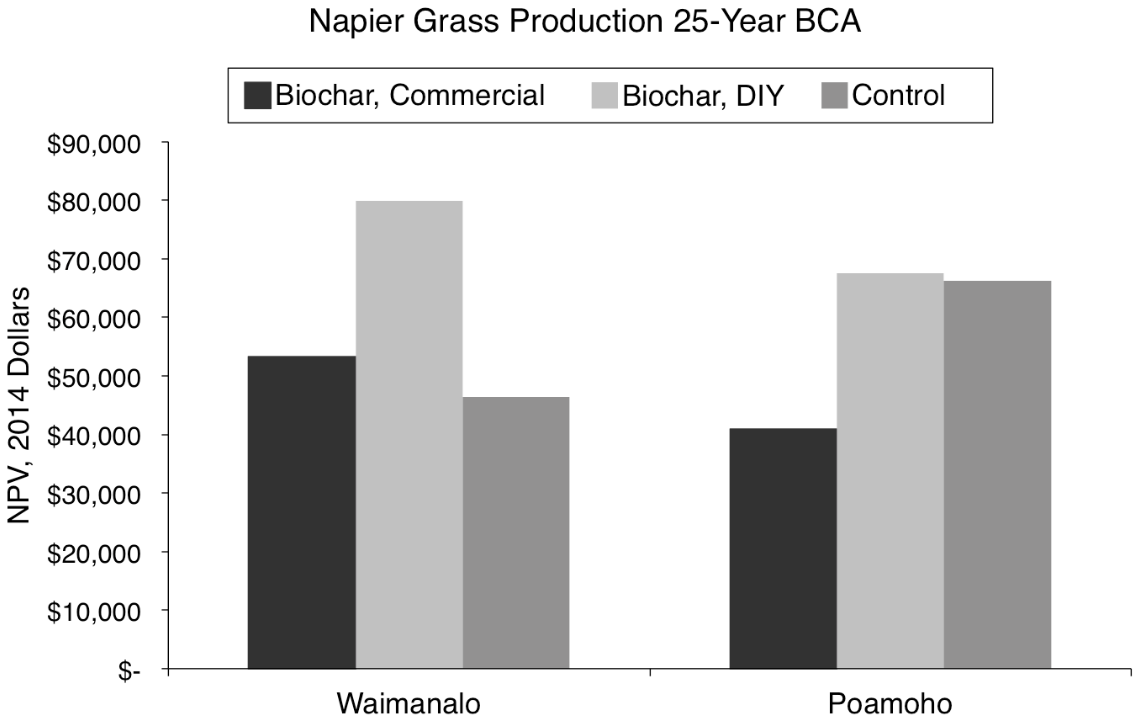

Figure 4.2. 25-year BCA of napier grass production, expressed as 2014 NPV, using adjusted crop yields and two contrasting biochar procurement scenarios.

Sensitivity analysis

Across all sites and crops, sensitivity analysis of the three key variables—CO_2e price, crop yield, and biochar investment cost—showed that crop yield was the most important variable affecting NPV of biochar amendment with a trend coefficient (ß) of 12.90 ± 0.86 (Figure 4.3). The price of CO_2e used in valuation of GWP was the next most important variable affecting NPV (ß = 10.01 ± 1.12), followed by biochar investment cost (ß = 7.88 ± 0.01). In the case of both crop yield and CO_2e price, sensitivity of NPV was different between cropping systems (Figures 4.4 & 4.5); compared to napier grass, crop yield was a less important factor in sweet corn, while CO_2e price was more important in sweet corn.

In regards to crop yield, although napier grass was a much less valuable crop per unit-area of production than sweet corn, increases in crop yields resulted in not only increased crop revenues, but also resulted in a higher economic value of GWP. Regarding CO_2e price, although napier grass had both smaller cumulative GHG emissions and possessed added value of crop biomass biofuel potential, the strong negative GWP value of sweet corn due to GHG emissions was still a greater factor in determining NPV.

Biochar investment cost had a very similar level of weight as a variable across crops and sites, because costs and the resulting absolute change in NPV were the same in all four systems (Figure 24). Although the DIY biochar scenario ranked much higher in terms of sustainability than the commercial biochar scenario, the investment cost of biochar was of lower importance as a variable than the other two variables when considered in terms of annual absolute value over the 25-year BCA period. The investment cost of biochar, although sometimes large, occurred only during the first year of production; other factors occurred annually, resulting in a much greater effect over the 25-year period. Therefore, the hypothesis that biochar investment cost would be the most important factor in determining the sustainability of the system was not supported; in fact, it was the least important factor. Crop yield proved to carry the most weight in controlling the NPV of the biochar system, followed by the CO_2e price used for GWP valuation.

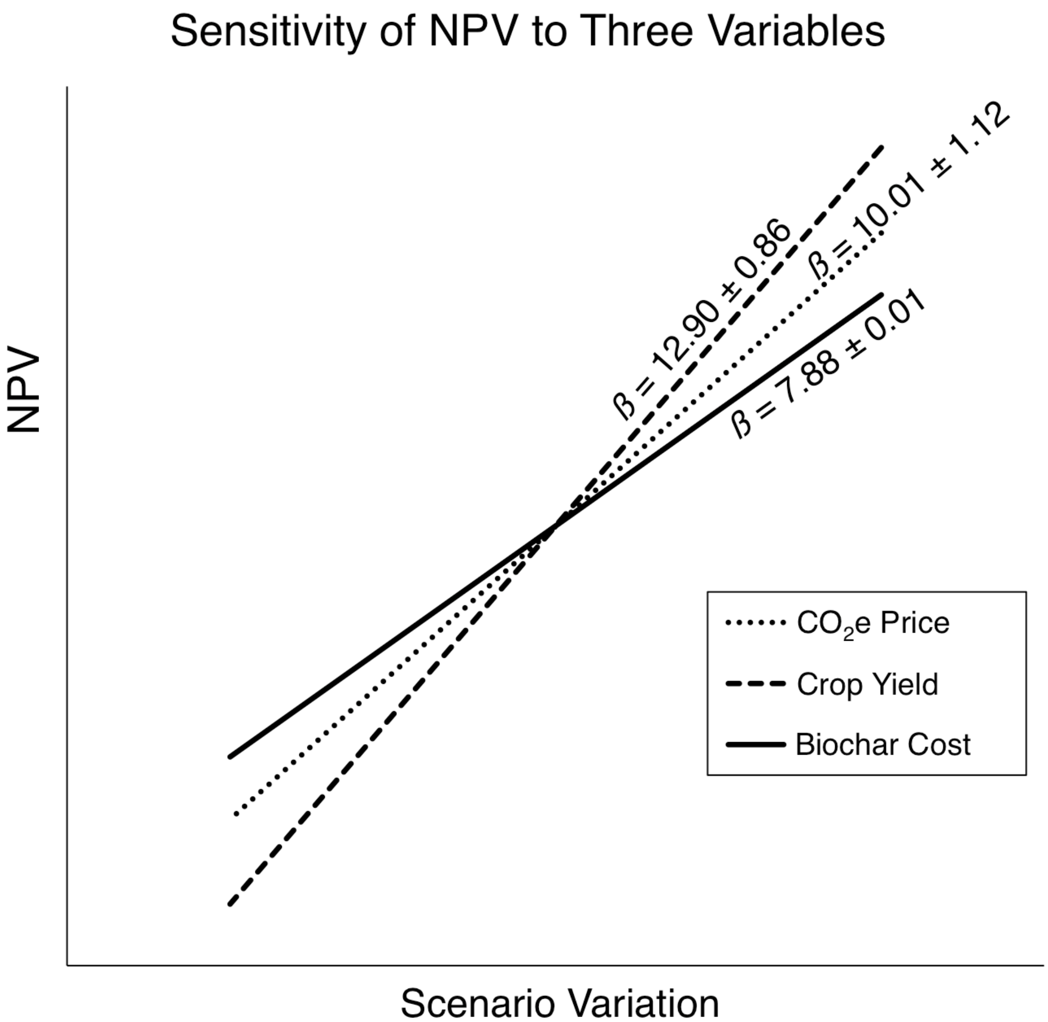

Figure 4.3. Visual depiction of the sensitivity of NPV to variation in three key variables. Axes are intentionally unitless and do not cross at zero in order to provide a simple visual representation of sensitivity, while lines and β values are empirically estimated. Beta values are the absolute values of the average slopes of the four crop and soil combinations. An increase of $1/ha/yr in these variables (GWP value, crop yield revenue, and biochar investment cost) will lead to an increase in NPV of β.

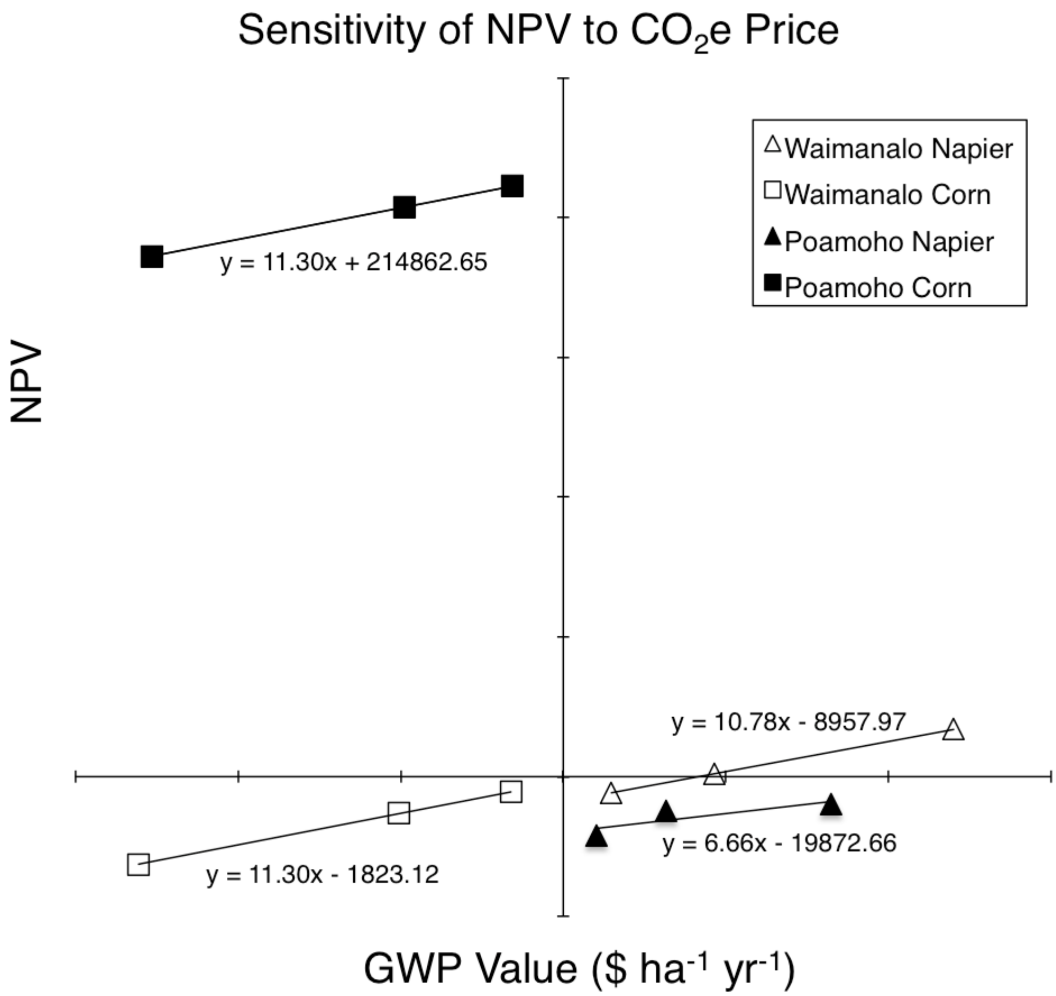

Figure 4.4. Sensitivity analysis of CO_2e price and NPV. An increase of $1/ha/yr in GWP value will lead to an increase in NPV according to the line slope.

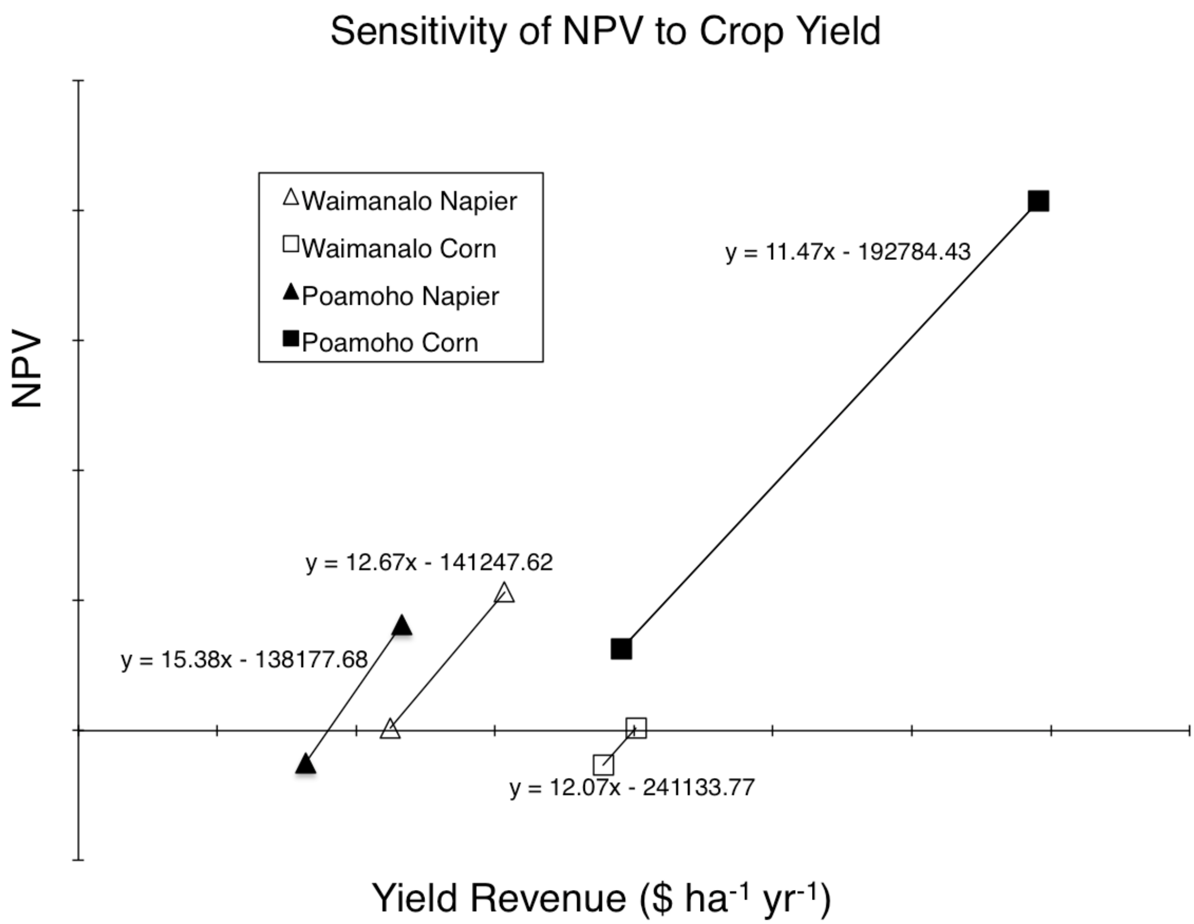

Figure 4.5. Sensitivity analysis of crop yields and NPV. An increase of $1/ha/yr in yield revenue will lead to an increase in NPV according to the line slope.

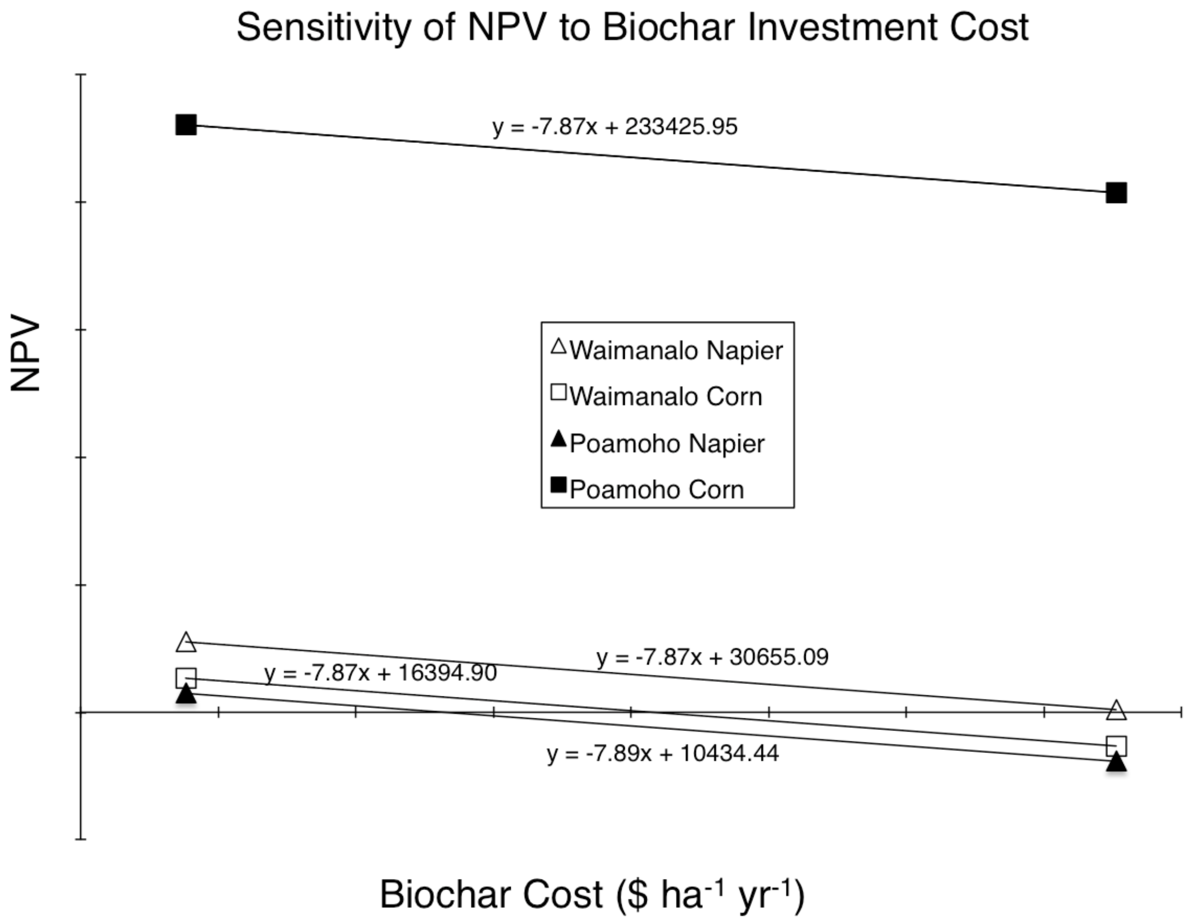

Figure 4.6. Sensitivity analysis of biochar investment cost and NPV. An increase of $1/ha/yr in biochar investment cost will lead to a decrease in NPV according to the line slope.

Chapter 5: Project Synthesis and Conclusion

Project synthesis

In variable scenario-testing BCA, it was shown that biochar amendment in sweet corn was not a sustainable option; biochar always lowered the NPV of the system because crop yields were negatively impacted at both sites. The effect of this yield reduction was strong enough to overpower any benefits to GWP from reduced GHG emissions, which occurred at Waimanalo (13% reduction in GWP over a 25-year period). Therefore, biochar amendment should not be pursued as a management option in sweet corn systems, unless there exists other evidence that crop yields would not be affected in the particular agroecosystem in question. If that were the case, then the GWP reduction seen at Waimanalo would be a significant benefit to the system NPV over the course of 25 years, and biochar amendment would be favorable under conditions of DIY scenario investment costs.

However, this recommendation is strictly limited by soil type—in the Oxisol at Poamoho, GWP was increased by 3% over a 25-year period due to augmented GHG emissions in the sweet corn crop. It is possible that this difference between sites could be due to the SOC content and the corresponding soil ecosystem inherent of the soil type prior to amendment. In the case of the two soils considered here, the effect of biochar on emissions of CO_2 and N_2O was inversely correlated with baseline soil C stock—higher-C soils had reduced emissions, while lower-C soils had increased emissions. Additionally, GHG emissions without biochar were naturally higher in the high-C Mollisol than in the low-C Oxisol. This means that, in the case of frequent tillage as used for sweet corn, biochar mitigated emissions and GWP in a soil with large natural (pre-biochar amendment) stocks and fluxes of C, but aggravated the same emissions and GWP in a soil with small stocks and fluxes of C. Based on this information, the effect of biochar amendment on GHG emissions and net GWP under frequent soil tillage could be predicted to be similar in soils according to their SOC content, although the precise microbial mechanism underlying this phenomenon is presently unclear.

Combined with BCA developed from alternative scenarios, sensitivity analysis revealed information about when biochar amendment could be a favorable option under hypothetical conditions of crops, soils, crop yields, CO_2e prices, and biochar investment costs. Although BCA showed that biochar amendment was not a sustainable option for sweet corn crops, sensitivity analysis revealed that the upfront investment cost of biochar was not as important of a factor in determining this outcome as were crop yields and GWP value. Crop yield provided the only absolute revenue present in Poamoho sweet corn; GWP value was positive only during the short term, and ultimately became negative during the course of the 25-year BCA as GHG emissions accumulated. GWP did provide a slight annual benefit to the Waimanalo system, but it was outweighed by reduction in crop yield. Biochar amendment would be more likely to become a sustainable option if effects on crop yields were more positive than if investment cost was lowered. Alternatively, if CO_2e prices were very small or zero in the case of Poamoho, or were very high in the case of Waimanalo, the feasibility of the biochar option would be more strongly impacted than by lowering biochar investment costs. Even if there hypothetically were no investment cost whatsoever of biochar amendment, the detrimental effects to yield alone (not to mention increased GWP at Poamoho) would render the option disadvantageous in the sweet corn cropping system.

Sensitivity analysis revealed contrasting implications for biofuel cropping systems, and especially wherein tillage is used sparingly, if at all, such as the ratoon-harvest napier grass crop. Though the relative importance of variables was the same between crops, sensitivity analysis showed that CO_2e price wielded less power in determining the BCA outcome than in sweet corn; concurrently, crop yield wielded more power than in sweet corn (Figures 4.4 & 4.5). This is despite the fact that napier grass GWP was continuously negative in biochar systems, providing a small additional annual revenue. The reason for these differences in variable weight between crops is owed to biochar crop yield effects. Compared to the reduction in crop yields seen with biochar amendment in sweet corn, yields were moderately increased in napier grass—resulting in both increased yield revenue and slightly increased GWP value. This doubly positive economic impact of increased yields in napier grass resulted in a modest shift of variable weight from CO_2e price to crop yields in comparison to non-biofuel sweet corn. Therefore, in consideration of biochar amendment in a biofuel cropping system, effects on crop yield should be regarded as possessing great significance. If negative GWP is valued positively whatsoever in a given biofuel cropping system, any yield gains achieved with biochar—as was seen in napier grass at both sites—will result in not only enhanced yield revenues, but additional benefit from decreased GWP. Then, after the degree of yield gain, the particular CO_2e price assigned to GWP takes over in determining the extent of the benefit.

While the napier grass system received a GWP benefit from the biofuel potential of its crop biomass, the sweet corn system did not receive any GWP benefits in this way—it was assumed to be produced strictly as a food crop for the purpose of this study. If crop GWP differences were taken out of context, it could appear to be suggested that biofuel crops are a more sustainable use of arable land than food crops. However, the scope of this study was not intended to be large enough to partake in this debate. The principal question was how biochar would impact the two systems differently, not whether food or fuel crops have greater merit in Hawaiian agriculture. If this were the case, the system boundaries would have to be greatly widened, and additional measures of social and environmental performance would have to be incorporated alongside GWP in order to assess the benefits of localized food production and issues of food security. The scope of this study was intentionally set small—limited to include only the farm enterprise itself—and GWP was used as an accessible means of quantifying sustainability based on climate change impacts at the farm level.

Biochar amendment was supported by adjusted yield BCA as a sustainable practice in the napier grass crop at both sites, although the payback period varied widely. Even though biochar investment cost was a less important factor than crop yield and CO_2e price in affecting NPV, it still played an important role in determining the degree of advantage of biochar over control treatments in terms of payback period. At Waimanalo, while NPV was higher than control in both biochar production scenarios (+15% in commercial, +72% in

DIY), the DIY production scenario had a much more pragmatic payback period—just 3 years, versus 30. At Poamoho, the DIY scenario outperformed the control with a large payback period, while the commercial scenario was infeasible. These differences between scenarios are owed solely to the investment cost incurred to the farmer of sourcing the biochar product.

In the last decade, many enterprises have emerged in hopes of commercially producing and selling biochar products to farmers, following the strategy of producers and retailers of thousands of other soil amendment products on the market today. However, the DIY scenario is clearly the preferred choice for the small-scale farmer who wishes to experiment with biochar amendment in their operations, even if there were strong evidence that suggested biochar would be a good investment regardless of how the product was procured. Simple, inexpensive methods of making biochar on a small scale are widely available to the public through reputable sources, such as the IBI. If feedstock can be sourced from on-farm biomass (without diverting it from other prudent uses) or from a waste stream present in the local community, then the resulting biochar scenario would be more likely to be a sustainable option for the farm operation than purchasing from a commercial source as evidenced by results of BCA. Of course, this suggestion must be explicitly underlain by the assumption that well tested methods of producing quality biochar are properly followed in the DIY scenario, and also by the assumption that the ensuing biochar amendment results in similar benefits to the system as was evidenced in this study.

Provided that evidence supports biochar amendment as a sustainable investment for a given cropping system, as in the case of napier grass, the best course of action for a farmer to take would be to procure a small amount of biochar via the least expensive means possible (assuming homogeneity of biochar quality) and to test amendment on a small experimental plot, not dissimilar to the methods deployed in this study. Depending on the type of crops of interest to the farmer, it would be prudent to test at least two different crops in the experiment. Throughout at least one growing season, crop yields should be closely monitored and compared to yields typically achieved on the farm, and assessed for potential revenues. Then, if the results are similar to the positive results seen in this study, the farmer could move incrementally from this small trial into larger-scale amendment. In any soil and crop combination, starting with a small experimental amendment trial helps, firstly, to establish or confirm that positive results are legitimate, and secondly, to avoid potentially large financial losses if adverse results occur, as in the case of sweet corn in this study.

Conclusion

Biochar amendment tended to decrease soil GHG emissions in the Mollisol, but increase emissions in the Oxisol; concurrently, biochar increased napier grass yields by 14%, yet decreased sweet corn yields by 6%. The combined effects on GWP value and yield revenue—plus biochar investment costs—increased NPV by as much as 73% over the control treatment in napier grass, resulting in a sustainable biochar system. In sweet corn, however, the best-case biochar scenario still decreased NPV by 31%—no matter how GWP was valued in terms of $/t$CO_2$e, any mitigation of GWP that did occur could not outweigh the effect of corn yield reductions. In all, the most important factor was how biochar affected crop yields (ß=12.90±0.86), followed by GWP value (ß=10.01±1.12) and biochar investment cost (ß=7.88±0.01).

Biochar amendment was shown to be an unsustainable option in a food crop with extensive tillage primarily because crop yields were negatively affected, irrespective of effects to the system's GWP. However, results also suggest that biochar could be a sustainable management option in grassy biofuel cropping systems where minimal tillage is used, though constrained by soil type. For the average Hawaiian farmer, this means that investment in biochar should be carefully considered, despite its burgeoning popularity. This study showed that the best prospect for biochar amendment in Hawaiian agriculture is for no-till or minimum-tillage crops, such as perennial bioenergy feedstocks, grown in naturally fertile soils similar to the Mollisol. Although these results add to the locally relevant body of knowledge, there is still much work to be done before off-the-shelf recommendations can be made for biochar use in the islands' agriculture; too much variation exists in the performance of biochar in different combinations of soils, crops, and managements, as was observed in this study and overwhelmingly has been the case found around the world.

Future local experimentation of biochar amendment should be tailor-made to target applications in specific agricultural sectors relevant in the state, to a degree even greater than was attempted in this study. Careful preliminary assessment should be used to identify not only combinations of soils, crops, and managements of dominant importance in the state's agricultural sector, but should also employ biochar made from feedstocks that possess strong potential locally, such as macadamia nut shell waste or invasive algal biomass. This will ensure that any results, whether positive or negative, have direct, immediate applicability and relevancy to real producers in the state. Lastly, future studies investigating biochar amendment should use methods that combine social, environmental, and economic components into a multidisciplinary assessment; in this study, this approach proved to yield valuable insight into relationships, tradeoffs, and feedbacks between system components that would largely remain hidden from plain sight using traditional disciplinary tools of assessment alone. Biochar amendment needs to be viewed in the context of a complex, integrated system where agronomic, ecologic, and socioeconomic factors are inseparable from one another. Understanding the linkages between these factors is critical for assessing the sustainability of biochar amendment in agricultural systems anywhere in the world.

APPENDIX

Appendix A. Weather and irrigation data

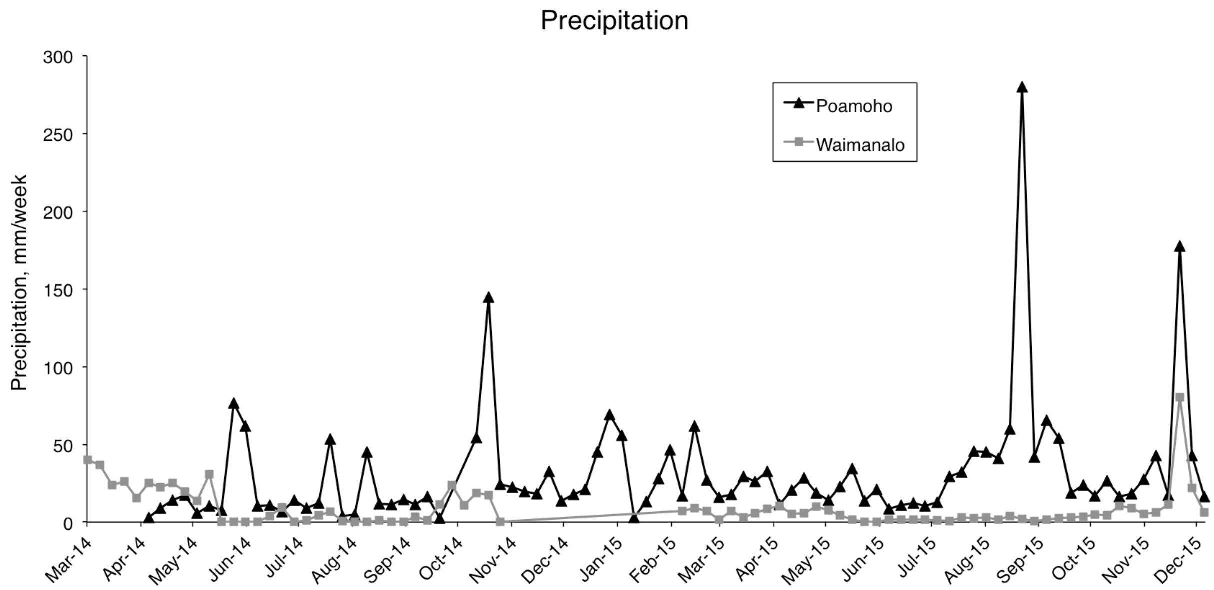

Figure 6.1. Weekly precipitation at Waimanalo and Poamoho field sites, recorded by weather stations in close proximity to field trials, from March 2014 to December 2015.

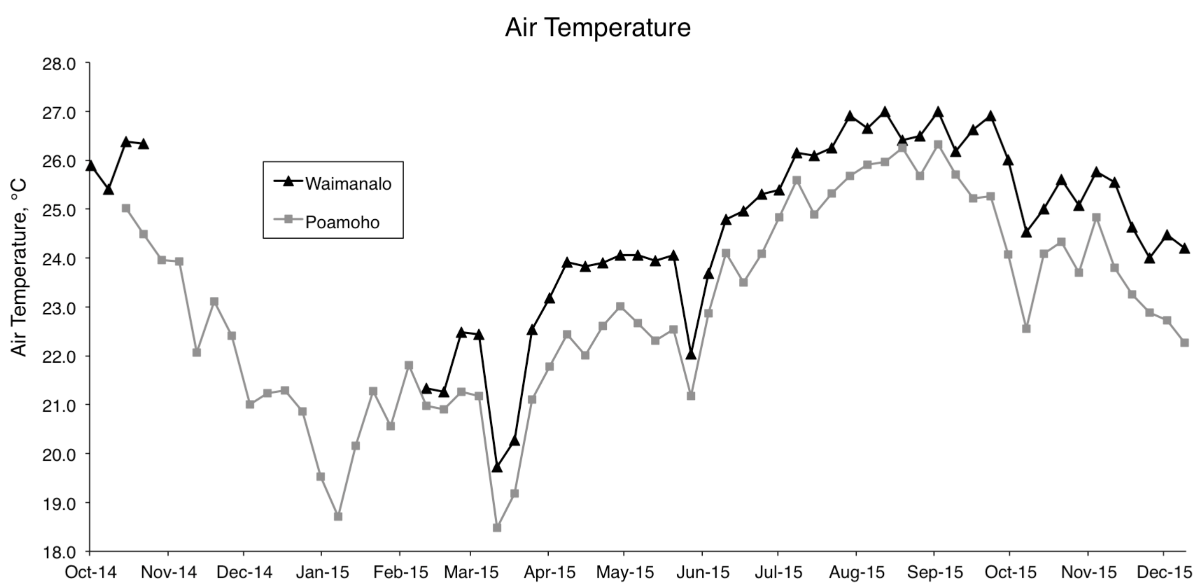

Figure 6.2. Average weekly air temperature at Waimanalo and Poamoho field sites, October 2014 to December 2015.

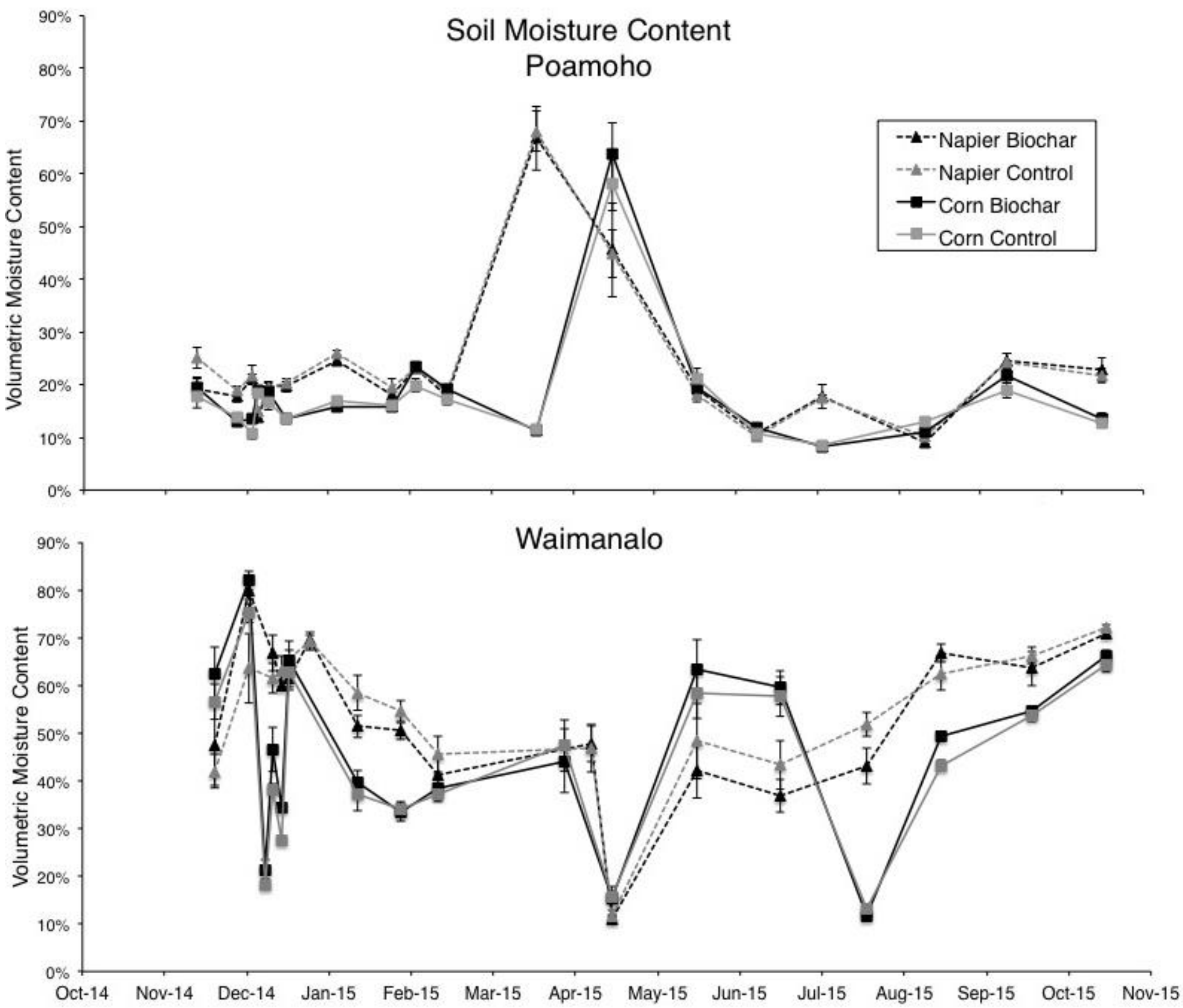

Figure 6.3. Soil moisture content at Waimanalo and Poamoho field sites, October 2014 to November 2015.

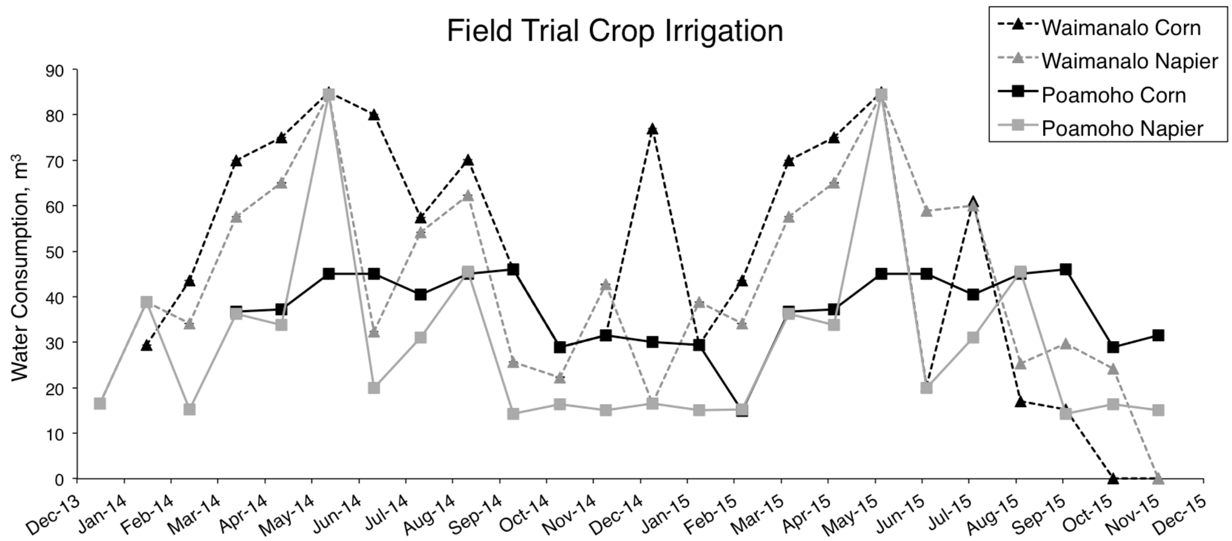

Figure 6.4. Monthly water consumption for irrigation of field trial crops, January 2014 to December 2015.

Appendix B. GWP and economic valuation tables

Poamoho Napier Grass, Control Scenario	Item	GWP Mg CO2e/ha	Price $/Mg CO2e	Value $/ha/yr	Net Value $/ha/yr
Low	Mgmt practices	0.50	$(12.97)	$(6.44)	
	GHGs	19.58	$(12.97)	$(253.91)	
	Biomass	40.24	$12.97	$521.82	
					$261.47
Medium	Mgmt practices	0.50	$(40.60)	$(20.16)	
	GHGs	19.58	$(40.60)	$(794.92)	
	Biomass	40.24	$40.60	$1,633.69	
					$818.60
High	Mgmt practices	0.50	$(105.03)	$(52.17)	
	GHGs	19.58	$(105.03)	$(2,056.65)	
	Biomass	40.24	$105.03	$4,226.71	
					$2,117.89

Table 6.1. GWP valuation of control treatment napier grass at Poamoho with three price scenarios.

Poamoho Napier Grass, Biochar					Year 1	Year 2
		GWP	Price	Value	Net Value	
Scenario	Item	Mg CO2e/ha	$/Mg CO2e	$/ha/yr	$/ha/yr	
Low	Fossil fuel	0.50	$(12.97)	$(6.44)		
	GHGs	21.56	$(12.97)	$(279.51)		
	Biochar	48.70	$12.97	$631.50		
	Biomass	42.89	$12.97	$556.15		
					$901.70	$270.20
Medium	Fossil fuel	0.50	$(40.60)	$(20.16)		
	GHGs	21.56	$(40.60)	$(875.08)		
	Biochar	48.70	$40.60	$1,977.09		
	Biomass	42.89	$40.60	$1,741.17		
					$2,823.02	$845.93
High	Fossil fuel	0.50	$(105.03)	$(52.17)		
	GHGs	21.56	$(105.03)	$(2,264.02)		
	Biochar	48.70	$105.03	$5,115.17		
	Biomass	42.89	$105.03	$4,504.80		
					$7,303.78	$2,188.61

Table 6.2. GWP valuation of biochar treatment napier grass at Poamoho with three price scenarios.

Waimanalo Napier Grass, Control					
		GWP	Price	Value	Net Value
Scenario	Item	Mg CO2e/ha	$/Mg CO2e	$/ha/yr	$/ha/yr
Low	Mgmt practices	0.50	$(12.97)	$(6.44)	
	GHGs	30.88	$(12.97)	$(400.48)	
	Biomass	49.76	$12.97	$645.23	
					$238.32
Medium	Mgmt practices	0.50	$(40.60)	$(20.16)	
	GHGs	30.88	$(40.60)	$(1,253.80)	
	Biomass	49.76	$40.60	$2,020.08	
					$746.12
High	Mgmt practices	0.50	$(105.03)	$(52.17)	
	GHGs	30.88	$(105.03)	$(3,243.86)	
	Biomass	49.76	$105.03	$5,226.40	
					$1,930.37

Table 6.3. GWP valuation of control treatment napier grass at Waimanalo with three price scenarios.

Waimanalo Napier Grass, Biochar					Year 1	Year 2
		GWP	Price	Value	Net Value	
Scenario	Item	Mg CO2e/ha	$/Mg CO2e	$/ha/yr	$/ha/yr	
Low	Fossil fuel	0.50	$(12.97)	$(6.44)		
	GHGs	30.32	$(12.97)	$(393.10)		
	Biochar	48.70	$12.97	$631.50		
	Biomass	60.05	$12.97	$778.63		
					$1,010.59	$379.09
Medium	Fossil fuel	0.50	$(40.60)	$(20.16)		
	GHGs	30.32	$(40.60)	$(1,230.71)		
	Biochar	48.70	$40.60	$1,977.09		
	Biomass	60.05	$40.60	$2,437.70		
					$3,163.92	$1,186.83
High	Fossil fuel	0.50	$(105.03)	$(52.17)		
	GHGs	30.32	$(105.03)	$(3,184.12)		
	Biochar	48.70	$105.03	$5,115.17		
	Biomass	60.05	$105.03	$6,306.89		
					$8,185.76	$3,070.59

Table 6.4. GWP valuation of biochar treatment napier grass at Waimanalo with three price scenarios.

Poamoho Sweet Corn, Control		GWP	Price	Value	Net Value
Scenario	Item	Mg CO2e/ha	$/Mg CO2e	$/ha/yr	$/ha/yr
Low	Mgmt practices	0.77	$(12.97)	$(10.02)	
	GHGs	22.56	$(12.97)	$(292.59)	
					$(302.61)
Medium	Mgmt practices	0.77	$(40.60)	$(31.37)	
	GHGs	22.56	$(40.60)	$(916.03)	
					$(947.40)
High	Mgmt practices	0.77	$(105.03)	$(81.15)	
	GHGs	22.56	$(105.03)	$(2,369.98)	
					$(2,451.13)

Table 6.5. GWP valuation of control treatment sweet corn at Poamoho with three price scenarios.

Poamoho Sweet Corn, Biochar					Year 1	Year 2
		GWP	Price	Value	Net Value	
Scenario	Item	Mg CO2e/ha	$/Mg CO2e	$/ha/yr	$/ha/yr	
Low	Fossil fuel	0.77	$(12.97)	$(10.02)		
	GHGs	24.26	$(12.97)	$(314.57)		
	Biochar	48.70	$12.97	$631.50		
					$306.92	$(324.59)
Medium	Fossil fuel	0.77	$(40.60)	$(31.37)		
	GHGs	24.26	$(40.60)	$(984.84)		
	Biochar	48.70	$40.60	$1,977.09		
					$960.89	$(1,016.20)
High	Fossil fuel	0.77	$(105.03)	$(81.15)		
	GHGs	24.26	$(105.03)	$(2,547.99)		
	Biochar	48.70	$105.03	$5,115.17		
					$2,486.03	$(2,629.14)

Table 6.6. GWP valuation of biochar treatment sweet corn at Poamoho with three price scenarios.

Waimanalo Sweet Corn, Control					
		GWP	Price	Value	Net Value
Scenario	Item	Mg CO2e/ha	$/Mg CO2e	$/ha/yr	$/ha/yr
Low	Mgmt practices	0.77	$(12.97)	$(10.02)	
	GHGs	25.70	$(12.97)	$(333.25)	
					$(343.26)
Medium	Mgmt practices	0.77	$(40.60)	$(31.37)	
	GHGs	25.70	$(40.60)	$(1,043.32)	
					$(1,074.68)
High	Mgmt practices	0.77	$(105.03)	$(81.15)	
	GHGs	25.70	$(105.03)	$(2,699.29)	
					$(2,780.44)

Table 6.7. GWP valuation of control treatment sweet corn at Waimanalo with three price scenarios.

Waimanalo Sweet Corn, Biochar					Year 1	Year 2
		GWP	Price	Value	Net Value	
Scenario	Item	Mg CO2e/ha	$/Mg CO2e	$/ha/yr	$/ha/yr	
Low	Fossil fuel	0.77	$(12.97)	$(10.02)		
	GHGs	25.00	$(12.97)	$(324.17)		
	Biochar	48.70	$12.97	$631.50		
					$297.32	$(334.18)
Medium	Fossil fuel	0.77	$(40.60)	$(31.37)		
	GHGs	25.00	$(40.60)	$(1,014.89)		
	Biochar	48.70	$40.60	$1,977.09		
					$930.83	$(1,046.25)
High	Fossil fuel	0.77	$(105.03)	$(81.15)		
	GHGs	25.00	$(105.03)	$(2,625.74)		
	Biochar	48.70	$105.03	$5,115.17		
					$2,408.28	$(2,706.89)

Table 6.8. GWP valuation of biochar treatment sweet corn at Waimanalo with three price scenarios.

Appendix C. Cumulative soil C stock figures

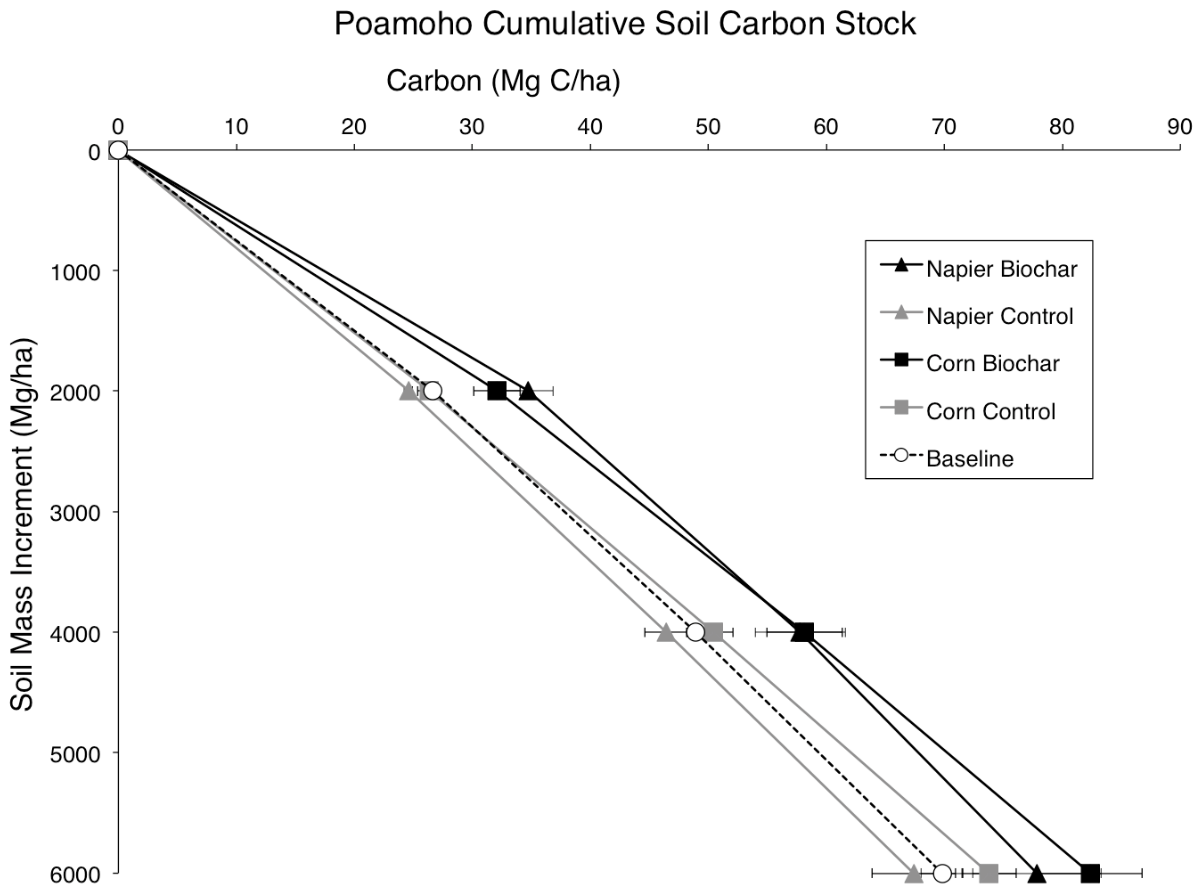

Figure 6.5. Cumulative soil C stock by soil mass increment at Poamoho, 21 months after start of field trials compared to baseline in September 2013.

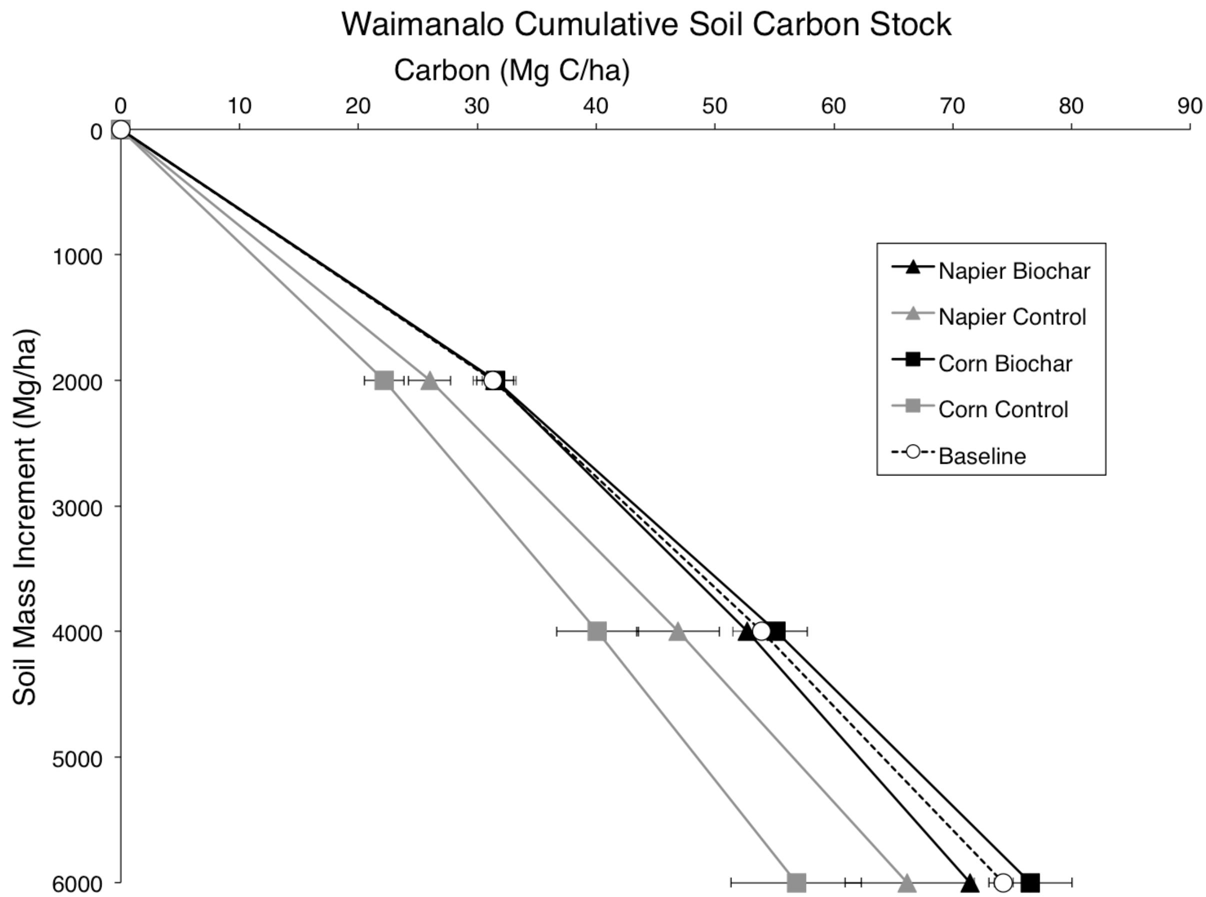

Figure 6.6. Cumulative soil C stock by soil mass increment at Waimanalo, 21 months after start of field trials compared to baseline in September 2013.

Appendix D. Year one and two primary BCA tables

Waimanalo Napier Year One 2013-2014 (Field trial yields)	Unit	Biochar		Control
		Commercial	DIY	
1. Soil Preparation	$/ha	$194.35	$194.35	$194.35
2. Planting	$/ha	$440.50	$440.50	$440.50
3. Fertilizer	$/ha	$1,862.15	$1,862.15	$1,862.15
4. Irrigation	$/ha	$7,281.94	$7,281.94	$7,281.94
5. Harvest	$/ha	$388.70	$388.70	$388.70
6. Biochar	$/ha	$94,037.62	$9,548.13	NA
Total Costs	$/ha	$104,656.70	$20,163.15	$10,619.08
Fixed Cost for Machinery	$/ha	$451.44	$447.38	$451.44
Variable Cost	$/ha	$10,167.64	$10,167.64	$10,167.64
Biomass Revenue	$/ha	$12,746.76	$12,746.76	$10,606.70
CO_2e Valuation Scenarios				
Low	$/ha	$892.09	$892.09	$139.01
Medium	$/ha	$2,792.92	$2,792.92	$435.22
High	$/ha	$7,225.91	$7,225.91	$1,126.02
Net Revenue$_{Low}$	$/ha	$(91,017.85)	$(6,524.30)	$126.64
Net Revenue$_{Medium}$	$/ha	$(89,117.02)	$(4,623.47)	$422.85
Net Revenue$_{High}$	$/ha	$(84,684.03)	$(190.48)	$1,113.64

Waimanalo Napier Year Two 2014-2015 (Field trial yields)	Unit	Biochar	Control
1. Fertilizer	$/ha	$1,862.15	$1,862.15
2. Irrigation	$/ha	$6,724.93	$6,724.93
3. Harvest	$/ha	$388.70	$388.70
Total Costs	$/ha	$9,374.30	$9,374.30
Fixed Cost for Machinery	$/ha	$398.52	$398.52
Variable Cost	$/ha	$8,975.78	$8,975.78
Biomass Revenue	$/ha	$11,163.06	$9,166.96
CO_2e Valuation Scenarios			
Low	$/ha	$260.59	$139.01
Medium	$/ha	$815.83	$435.22
High	$/ha	$2,110.74	$1,126.02
Net Revenue$_{Low}$	$/ha	$2,049.34	$(68.32)
Net Revenue$_{Medium}$	$/ha	$2,604.59	$227.88
Net Revenue$_{High}$	$/ha	$3,899.50	$918.68

Table 6.9. Year one and two BCA of Waimanalo napier grass production, using yields obtained from field trials.

Poamoho Napier Year One 2013-2014 (Field trial yields)	Unit	Biochar		Control
		Commercial	DIY	
1. Soil Preparation	$/ha	$194.35	$194.35	$194.35
2. Planting	$/ha	$440.50	$440.50	$440.50
3. Fertilizer	$/ha	$2,185.07	$2,185.07	$2,185.07
4. Irrigation	$/ha	$4,989.76	$4,989.76	$4,989.76
5. Harvest	$/ha	$388.70	$388.70	$388.70
6. Biochar	$/ha	$94,037.62	$9,415.03	NA
Total Costs	$/ha	$102,596.72	$17,974.13	$8,559.10
Fixed Cost for Machinery	$/ha	$360.73	$360.73	$360.73
Variable Cost	$/ha	$8,198.37	$8,198.37	$8,198.37
Biomass Revenue	$/ha	$8,365.65	$8,365.65	$7,315.55
CO_2e Valuation Scenarios				
Low	$/ha	$802.37	$802.37	$177.14
Medium	$/ha	$2,512.03	$2,512.03	$554.60
High	$/ha	$6,499.18	$6,499.18	$1,434.87
Net Revenue$_{Low}$	$/ha	$(93,428.70)	$(8,806.11)	$(1,066.41)
Net Revenue$_{Medium}$	$/ha	$(91,719.03)	$(7,096.45)	$(688.95)
Net Revenue$_{High}$	$/ha	$(87,731.88)	$(3,109.30)	$191.32

Poamoho Napier Year Two 2014-2015 (Field trial yields)	Unit	Biochar	Control
1. Fertilizer	$/ha	$1,862.15	$1,862.15
2. Irrigation	$/ha	$4,666.42	$4,666.42
3. Harvest	$/ha	$388.70	$388.70
Total Costs	$/ha	$7,224.40	$7,224.40
Fixed Cost for Machinery	$/ha	$307.13	$307.13
Variable Cost	$/ha	$6,917.27	$6,917.27
Biomass Revenue	$/ha	$8,180.18	$8,530.40
CO_2e Valuation Scenarios			
Low	$/ha	$170.87	$177.14
Medium	$/ha	$534.94	$554.60
High	$/ha	$1,384.01	$1,434.87
Net Revenue$_{Low}$	$/ha	$1,126.65	$1,483.15
Net Revenue$_{Medium}$	$/ha	$1,490.73	$1,860.60
Net Revenue$_{High}$	$/ha	$2,339.80	$2,740.87

Table 6.10. Year one and two BCA of Poamoho napier grass production, using yields obtained from field trials.

Waimanalo Napier Year One 2013-2014 (Adjusted yields)	Unit	Biochar Commercial	Biochar DIY	Control
1. Soil Preparation	$/ha	$194.35	$194.35	$194.35
2. Planting	$/ha	$440.50	$440.50	$440.50
3. Fertilizer	$/ha	$1,862.15	$1,862.15	$1,862.15
4. Irrigation	$/ha	$7,281.94	$7,281.94	$7,281.94
5. Harvest	$/ha	$388.70	$388.70	$388.70
6. Biochar	$/ha	$94,037.62	$9,548.13	NA
Total Costs	$/ha	$104,656.70	$20,163.15	$10,619.08
Fixed Cost for Machinery	$/ha	$451.44	$447.38	$451.44
Variable Cost	$/ha	$10,167.64	$10,167.64	$10,167.64
Biomass Revenue	$/ha	$12,746.76	$12,746.76	$10,606.70
CO_2e Valuation Scenarios				
Low	$/ha	$1,010.59	$1,010.59	$238.32
Medium	$/ha	$3,163.92	$3,163.92	$746.12
High	$/ha	$8,185.76	$8,185.76	$1,930.37
Net Revenue$_{Low}$	$/ha	$(90,899.35)	$(6,405.80)	$225.94
Net Revenue$_{Medium}$	$/ha	$(88,746.02)	$(4,252.47)	$733.74
Net Revenue$_{High}$	$/ha	$(83,724.18)	$769.37	$1,918.00

Waimanalo Napier Year Two 2014-2015 (Adjusted yields)	Unit	Biochar	Control
1. Fertilizer	$/ha	$1,862.15	$1,862.15
2. Irrigation	$/ha	$6,724.93	$6,724.93
3. Harvest	$/ha	$388.70	$388.70
Total Costs	$/ha	$9,374.30	$9,374.30
Fixed Cost for Machinery	$/ha	$398.52	$398.52
Variable Cost	$/ha	$8,975.78	$8,975.78
Biomass Revenue	$/ha	$15,455.16	$12,763.71
CO_2e Valuation Scenarios			
Low	$/ha	$379.09	$238.32
Medium	$/ha	$1,186.83	$746.12
High	$/ha	$3,070.59	$1,930.37
Net Revenue$_{Low}$	$/ha	$6,459.94	$3,627.73
Net Revenue$_{Medium}$	$/ha	$7,267.69	$4,135.53
Net Revenue$_{High}$	$/ha	$9,151.45	$5,319.78

Table 6.11. Year one and two BCA of Waimanalo napier grass production, using adjusted crop yields.

Poamoho Napier Year One 2013-2014 (Adjusted yields)	Unit	Biochar Commercial	Biochar DIY	Control
1. Soil Preparation	$/ha	$194.35	$194.35	$194.35
2. Planting	$/ha	$440.50	$440.50	$440.50
3. Fertilizer	$/ha	$2,185.07	$2,185.07	$2,185.07
4. Irrigation	$/ha	$4,989.76	$4,989.76	$4,989.76
5. Harvest	$/ha	$388.70	$388.70	$388.70
6. Biochar	$/ha	$94,037.62	$9,415.03	NA
Total Costs	$/ha	$102,596.72	$17,974.13	$8,559.10
Fixed Cost for Machinery	$/ha	$360.73	$360.73	$360.73
Variable Cost	$/ha	$8,198.37	$8,198.37	$8,198.37
Biomass Revenue	$/ha	$8,365.65	$8,365.65	$7,315.55
CO_2e Valuation Scenarios				
Low	$/ha	$1,161.81	$1,161.81	$499.85
Medium	$/ha	$3,637.36	$3,637.36	$1,564.90
High	$/ha	$9,410.66	$9,410.66	$4,048.75
Net Revenue$_{Low}$	$/ha	$(93,069.25)	$(8,446.67)	$(743.70)
Net Revenue$_{Medium}$	$/ha	$(90,593.70)	$(5,971.12)	$321.35
Net Revenue$_{High}$	$/ha	$(84,820.40)	$(197.82)	$2,805.20

Poamoho Napier Year Two 2014-2015 (Adjusted yields)	Unit	Biochar	Control
1. Fertilizer	$/ha	$1,862.15	$1,862.15
2. Irrigation	$/ha	$4,666.42	$4,666.42
3. Harvest	$/ha	$388.70	$388.70
Total Costs	$/ha	$7,224.40	$7,224.40
Fixed Cost for Machinery	$/ha	$307.13	$307.13
Variable Cost	$/ha	$6,917.27	$6,917.27
Biomass Revenue	$/ha	$11,778.04	$11,584.63
CO_2e Valuation Scenarios			
Low	$/ha	$530.31	$499.85
Medium	$/ha	$1,660.27	$1,564.90
High	$/ha	$4,295.50	$4,048.75
Net Revenue$_{Low}$	$/ha	$5,083.95	$4,860.08
Net Revenue$_{Medium}$	$/ha	$6,213.91	$5,925.13
Net Revenue$_{High}$	$/ha	$8,849.14	$8,408.98

Table 6.12. Year one and two BCA of Poamoho napier grass production, using adjusted crop yields.

Waimanalo Corn Year One 2014-2015 (Field trial yields)	Unit	Biochar Commercial	Biochar DIY	Control
1. Soil Preparation	$/ha	$583.04	$583.04	$583.04
2. Planting	$/ha	$1,508.75	$1,508.75	$1,508.75
3. Fertilizer	$/ha	$3,882.97	$3,882.97	$3,882.97
4. Irrigation	$/ha	$8,382.38	$8,382.38	$8,382.38
5. Harvest	$/ha	$1,345.49	$1,345.49	$1,345.49
6. Biochar	$/ha	$94,037.62	$9,548.13	NA
Total Costs	$/ha	$110,431.16	$25,941.68	$16,393.55
Fixed Cost for Machinery	$/ha	$690.92	$690.92	$690.92
Variable Cost	$/ha	$15,702.63	$15,702.63	$15,702.63
Biomass Revenue	$/ha	$24,100.15	$24,100.15	$27,166.12
CO_2e Valuation Scenarios				
Low	$/ha	$297.32	$297.32	$(343.26)
Medium	$/ha	$930.83	$930.83	$(1,074.68)
High	$/ha	$2,408.28	$2,408.28	$(2,780.44)
Net Revenue$_{Low}$	$/ha	$(86,033.70)	$(1,544.21)	$10,429.30
Net Revenue$_{Medium}$	$/ha	$(85,400.18)	$(910.70)	$9,697.88
Net Revenue$_{High}$	$/ha	$(83,922.74)	$566.75	$7,992.12

Waimanalo Corn Year Two 2015-2016 (Field trial yields)	Unit	Biochar	Control
1. Soil Preparation	$/ha	$583.04	$583.04
2. Planting	$/ha	$1,508.75	$1,508.75
3. Fertilizer	$/ha	$3,882.97	$3,882.97
4. Irrigation	$/ha	$8,382.38	$8,382.38
5. Harvest	$/ha	$1,345.49	$1,345.49
Total Costs	$/ha	$16,399.83	$16,399.83
Fixed Cost for Machinery	$/ha	$697.20	$697.20
Variable Cost	$/ha	$15,702.63	$15,702.63
Biomass Revenue	$/ha	$18,669.86	$20,040.13
CO_2e Valuation Scenarios			
Low	$/ha	$(334.18)	$(343.26)
Medium	$/ha	$(1,046.25)	$(1,074.68)
High	$/ha	$(2,706.89)	$(2,780.44)
Net Revenue$_{Low}$	$/ha	$1,935.85	$3,297.03
Net Revenue$_{Medium}$	$/ha	$1,223.78	$2,565.61
Net Revenue$_{High}$	$/ha	$(436.86)	$859.85

Table 6.13. Year one and two BCA of Waimanalo sweet corn production, using yields obtained from field trials.

Poamoho Corn Year One 2014-2015 (Field trial yields)	Unit	Biochar Commercial	Biochar DIY	Control
1. Soil Preparation	$/ha	$583.04	$583.04	$583.04
2. Planting	$/ha	$1,563.00	$1,563.00	$1,563.00
3. Fertilizer	$/ha	$4,205.89	$4,205.89	$4,205.89
4. Irrigation	$/ha	$4,835.15	$4,835.15	$4,835.15
5. Harvest	$/ha	$1,345.49	$1,345.49	$1,345.49
6. Pesticide	$/ha	$167.21	$167.21	$167.21
7. Biochar	$/ha	$94,037.62	$9,548.13	NA
Total Costs	$/ha	$107,296.18	$22,806.70	$13,258.57
Fixed Cost for Machinery	$/ha	$558.79	$558.79	$558.79
Variable Cost	$/ha	$12,699.78	$12,699.78	$12,699.78
Biomass Revenue	$/ha	$36,917.94	$36,917.94	$39,317.12
CO_2e Valuation Scenarios				
Low	$/ha	$306.92	$306.92	$(302.61)
Medium	$/ha	$960.89	$960.89	$(947.40)
High	$/ha	$2,486.03	$2,486.03	$(2,451.13)
Net Revenue$_{Low}$	$/ha	$(70,071.33)	$14,418.16	$25,755.95
Net Revenue$_{Medium}$	$/ha	$(69,417.36)	$15,072.13	$25,111.16
Net Revenue$_{High}$	$/ha	$(67,892.22)	$16,597.27	$23,607.43

Poamoho Corn Year Two 2015-2016 (Field trial yields)	Unit	Biochar	Control
1. Soil Preparation	$/ha	$583.04	$583.04
2. Planting	$/ha	$1,563.00	$1,563.00
3. Fertilizer	$/ha	$4,205.89	$4,205.89
4. Irrigation	$/ha	$4,835.15	$4,835.15
5. Harvest	$/ha	$1,345.49	$1,345.49
6. Pesticide	$/ha	$167.21	$167.21
Total Costs	$/ha	$13,258.57	$13,258.57
Fixed Cost for Machinery	$/ha	$558.79	$558.79
Variable Cost	$/ha	$12,699.78	$12,699.78
Biomass Revenue	$/ha	$34,470.73	$37,168.44
CO_2e Valuation Scenarios			
Low	$/ha	$(324.59)	$(302.61)
Medium	$/ha	$(1,016.20)	$(947.40)
High	$/ha	$(2,629.14)	$(2,451.13)
Net Revenue$_{Low}$	$/ha	$20,887.58	$23,607.26
Net Revenue$_{Medium}$	$/ha	$20,195.96	$22,962.47
Net Revenue$_{High}$	$/ha	$18,583.02	$21,458.74

Table 6.14. Year one and two BCA of Poamoho sweet corn production, using yields obtained from field trials.

Waimanalo Corn Year One 2014-2015 (Adjusted yields)	Unit	Biochar Commercial	Biochar DIY	Control
1. Soil Preparation	$/ha	$388.70	$388.70	$388.70
2. Planting	$/ha	$1,508.75	$1,508.75	$1,508.75
3. Fertilizer	$/ha	$3,882.97	$3,882.97	$3,882.97
4. Irrigation	$/ha	$8,382.38	$8,382.38	$8,382.38
5. Harvest	$/ha	$1,345.49	$1,345.49	$1,345.49
6. Biochar	$/ha	$94,037.62	$9,548.13	NA
Total Costs	$/ha	$110,228.26	$25,738.78	$16,190.65
Fixed Cost for Machinery	$/ha	$682.36	$682.36	$682.36
Variable Cost	$/ha	$15,508.28	$15,508.28	$15,508.28
Biomass Revenue	$/ha	$21,188.55	$21,188.55	$21,478.90
CO2e Valuation Scenarios				
Low	$/ha	$297.32	$297.32	$(343.26)
Medium	$/ha	$930.83	$930.83	$(1,074.68)
High	$/ha	$2,408.28	$2,408.28	$(2,780.44)
Net RevenueLow	$/ha	$(88,742.40)	$(4,252.91)	$4,944.99
Net RevenueMedium	$/ha	$(88,108.88)	$(3,619.40)	$4,213.57
Net RevenueHigh	$/ha	$(86,631.44)	$(2,141.96)	$2,507.81

Waimanalo Corn Year Two 2015-2016 (Adjusted yields)	Unit	Biochar	Control
1. Soil Preparation	$/ha	$583.04	$583.04
2. Planting	$/ha	$1,508.75	$1,508.75
3. Fertilizer	$/ha	$3,882.97	$3,882.97
4. Irrigation	$/ha	$8,382.38	$8,382.38
5. Harvest	$/ha	$1,345.49	$1,345.49
Total Costs	$/ha	$16,399.83	$16,399.83
Fixed Cost for Machinery	$/ha	$697.20	$697.20
Variable Cost	$/ha	$15,702.63	$15,702.63
Biomass Revenue	$/ha	$20,015.94	$21,478.90
CO2e Valuation Scenarios			
Low	$/ha	$(334.18)	$(343.26)
Medium	$/ha	$(1,046.25)	$(1,074.68)
High	$/ha	$(2,706.89)	$(2,780.44)
Net RevenueLow	$/ha	$3,281.93	$4,735.81
Net RevenueMedium	$/ha	$2,569.86	$4,004.39
Net RevenueHigh	$/ha	$909.22	$2,298.63

Table 6.15. Year one and two BCA of Waimanalo sweet corn production, using adjusted crop yields.

Poamoho Corn Year One 2014-2015 (Adjusted yields)	Unit	Biochar Commercial	Biochar DIY	Control
1. Soil Preparation	$/ha	$388.70	$388.70	$388.70
2. Planting	$/ha	$1,563.00	$1,563.00	$1,563.00
3. Fertilizer	$/ha	$4,205.89	$4,205.89	$4,205.89
4. Irrigation	$/ha	$4,835.15	$4,835.15	$4,835.15
5. Harvest	$/ha	$1,345.49	$1,345.49	$1,345.49
6. Pesticide	$/ha	$167.21	$167.21	$167.21
7. Biochar	$/ha	$94,037.62	$9,548.13	NA
Total Costs	$/ha	$107,093.28	$22,603.80	$13,055.67
Fixed Cost for Machinery	$/ha	$550.24	$550.24	$550.24
Variable Cost	$/ha	$12,505.43	$12,505.43	$12,505.43
Biomass Revenue	$/ha	$20,673.97	$20,673.97	$21,478.90
CO_2e Valuation Scenarios				
Low	$/ha	$306.92	$306.92	$(302.61)
Medium	$/ha	$960.89	$960.89	$(947.40)
High	$/ha	$2,486.03	$2,486.03	$(2,451.13)
Net $Revenue_{Low}$	$/ha	$(86,112.40)	$(1,622.91)	$8,120.63
Net $Revenue_{Medium}$	$/ha	$(85,458.43)	$(968.94)	$7,475.84
Net $Revenue_{High}$	$/ha	$(83,933.29)	$556.20	$5,972.10

Poamoho Corn Year Two 2015-2016 (Adjusted yields)	Unit	Biochar	Control
1. Soil Preparation	$/ha	$583.04	$583.04
2. Planting	$/ha	$1,563.00	$1,563.00
3. Fertilizer	$/ha	$4,205.89	$4,205.89
4. Irrigation	$/ha	$4,835.15	$4,835.15
5. Harvest	$/ha	$1,345.49	$1,345.49
6. Pesticide	$/ha	$167.21	$167.21
Total Costs	$/ha	$13,258.57	$13,258.57
Fixed Cost for Machinery	$/ha	$558.79	$558.79
Variable Cost	$/ha	$12,699.78	$12,699.78
Biomass Revenue	$/ha	$19,487.78	$21,478.90
CO_2e Valuation Scenarios			
Low	$/ha	$(324.59)	$(302.61)
Medium	$/ha	$(1,016.20)	$(947.40)
High	$/ha	$(2,629.14)	$(2,451.13)
Net $Revenue_{Low}$	$/ha	$5,904.63	$7,917.73
Net $Revenue_{Medium}$	$/ha	$5,213.02	$7,272.94
Net $Revenue_{High}$	$/ha	$3,600.08	$5,769.21

Table 6.16. Year one and two BCA of Poamoho sweet corn production, using adjusted crop yields.

Appendix E. Alternative scenarios BCA figures

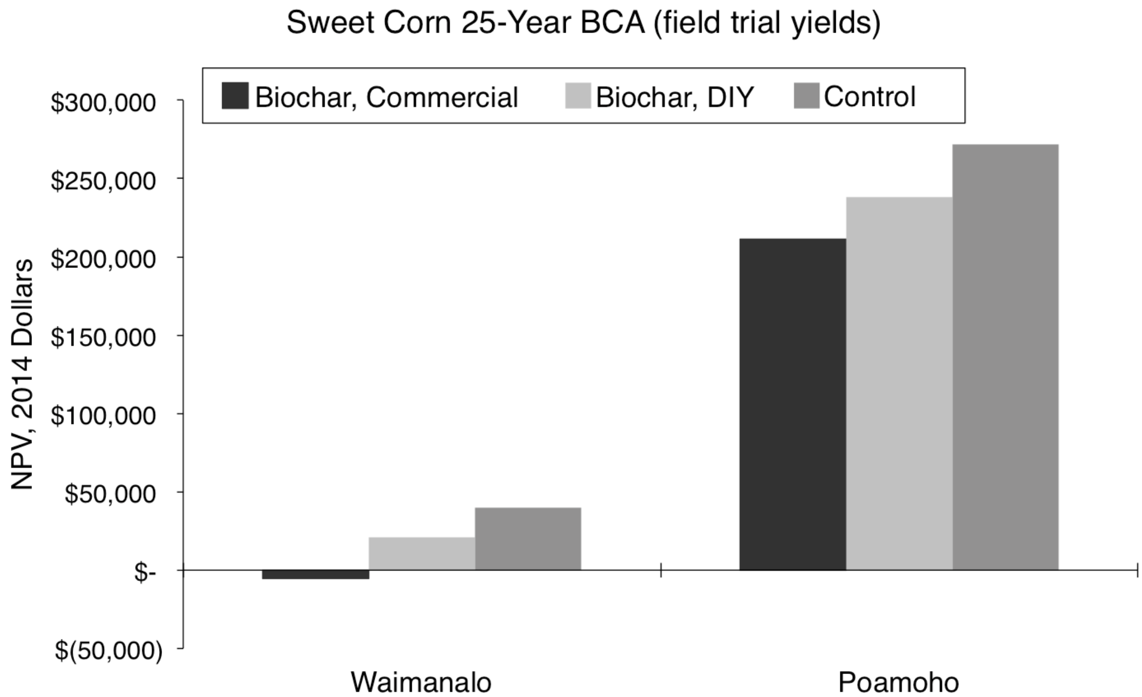

Figure 6.7. Sweet corn production BCA, low GWP valuation scenario and field trial yields.

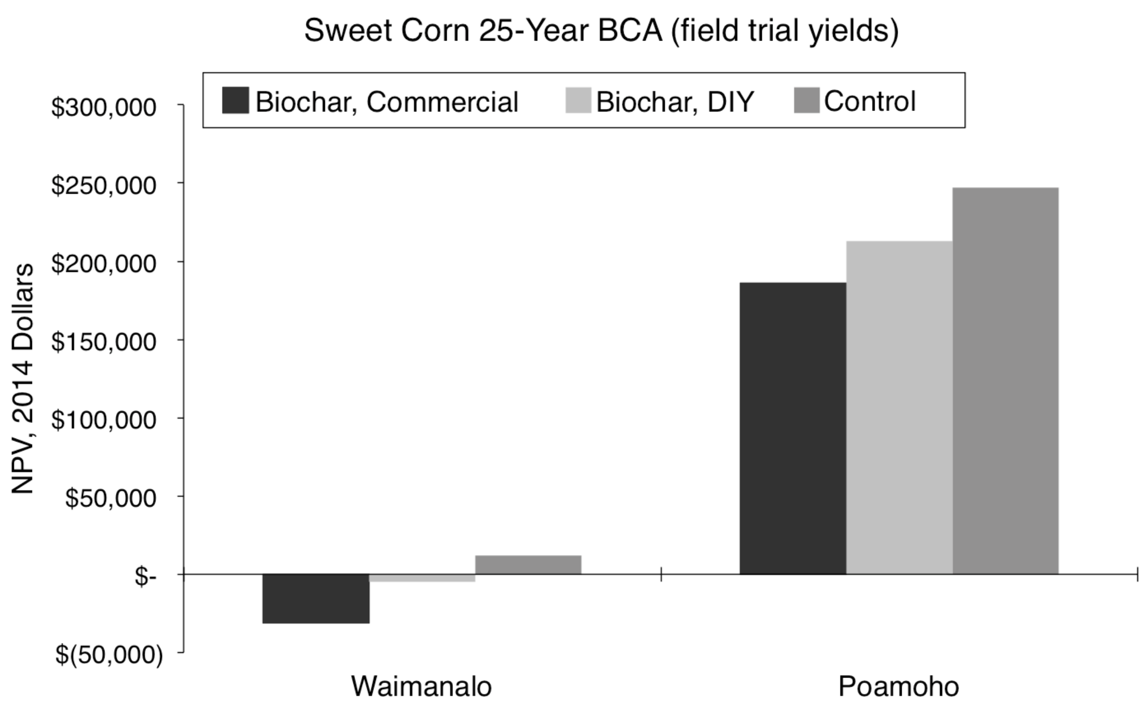

Figure 6.8. Sweet corn production BCA, high GWP valuation scenario and field trial yields.

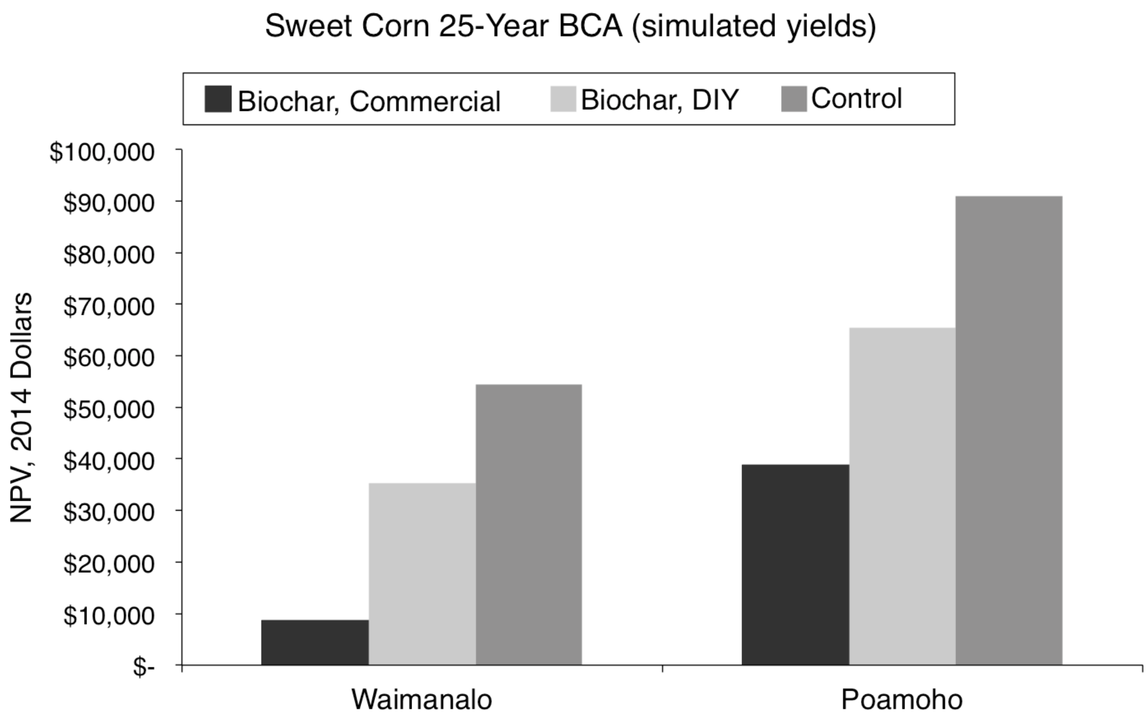

Figure 6.9. Sweet corn production BCA, low GWP valuation scenario and adjusted yields.

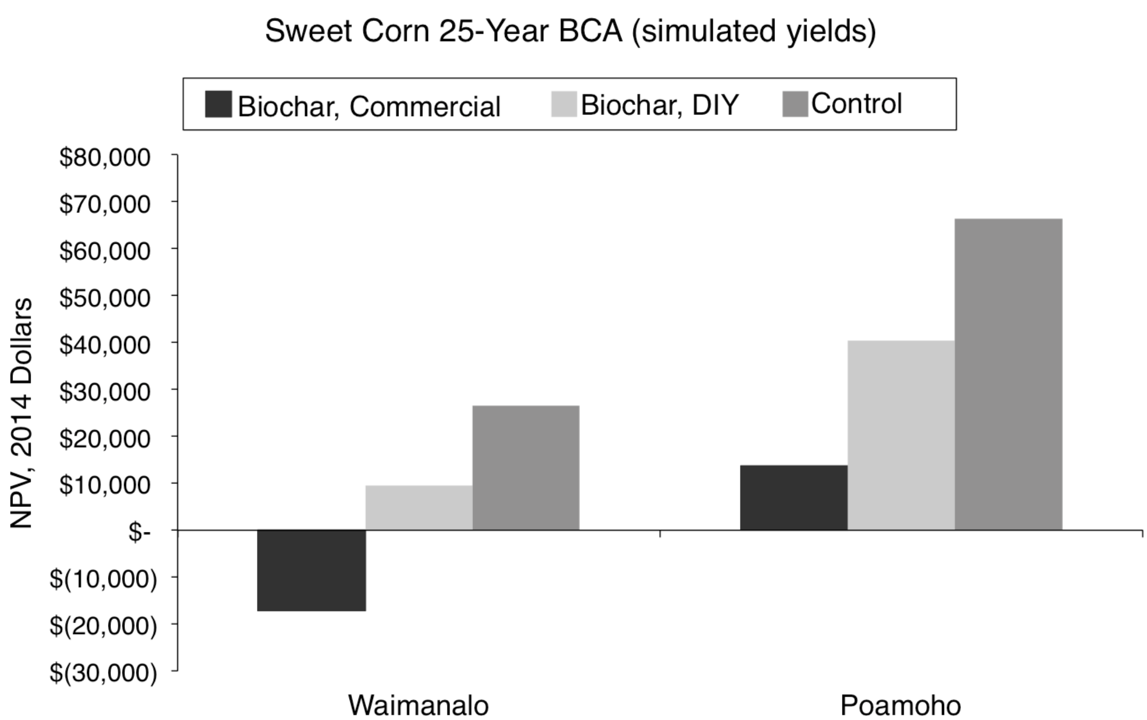

Figure 6.10. Sweet corn production BCA, high GWP valuation scenario and adjusted yields.

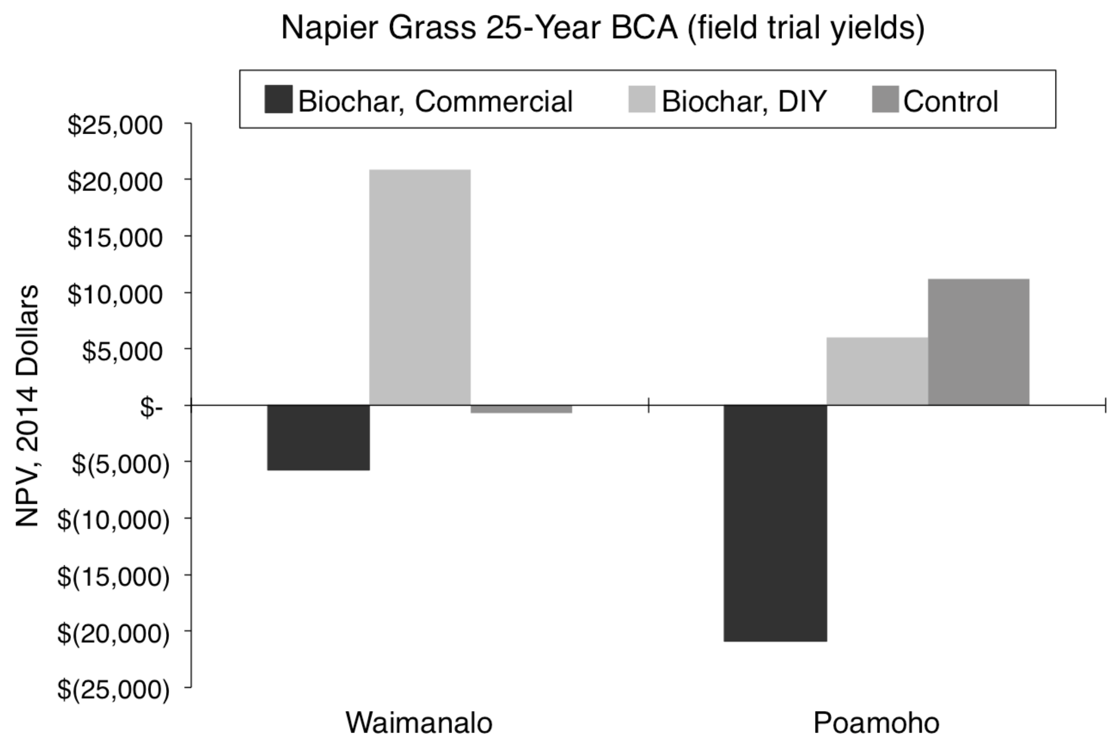

Figure 6.11. Napier grass production BCA, low GWP valuation scenario and field trial yields.

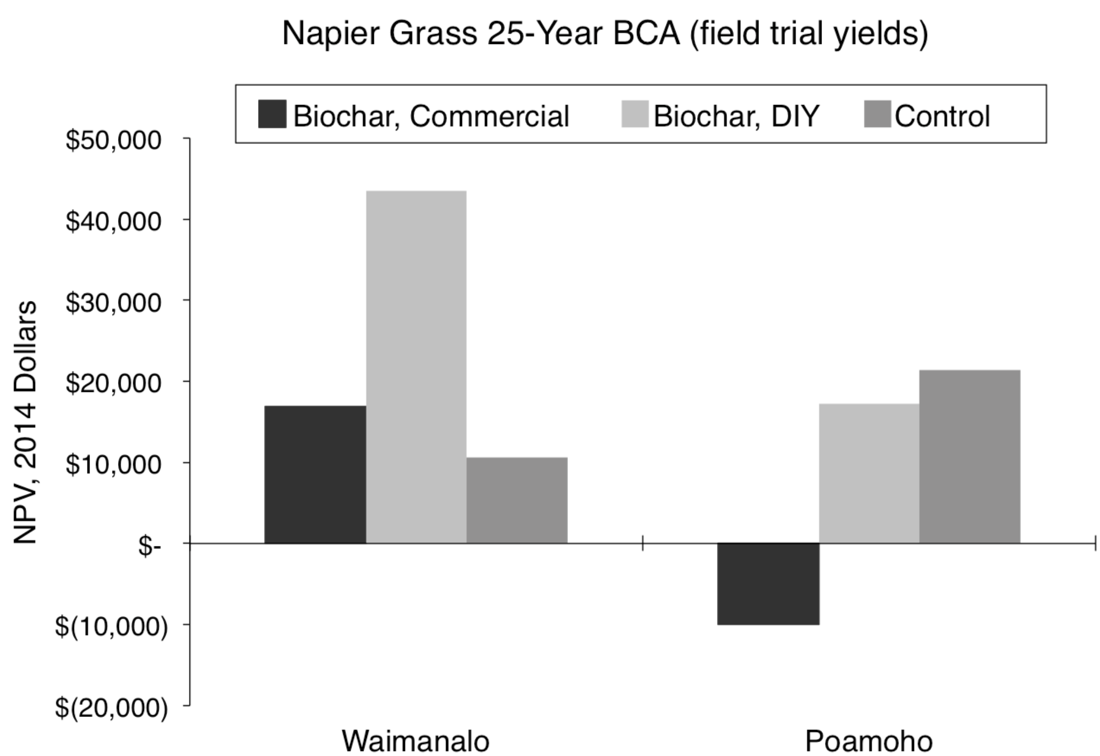

Figure 6.12. Napier grass production BCA, high GWP valuation scenario and field trial yields.

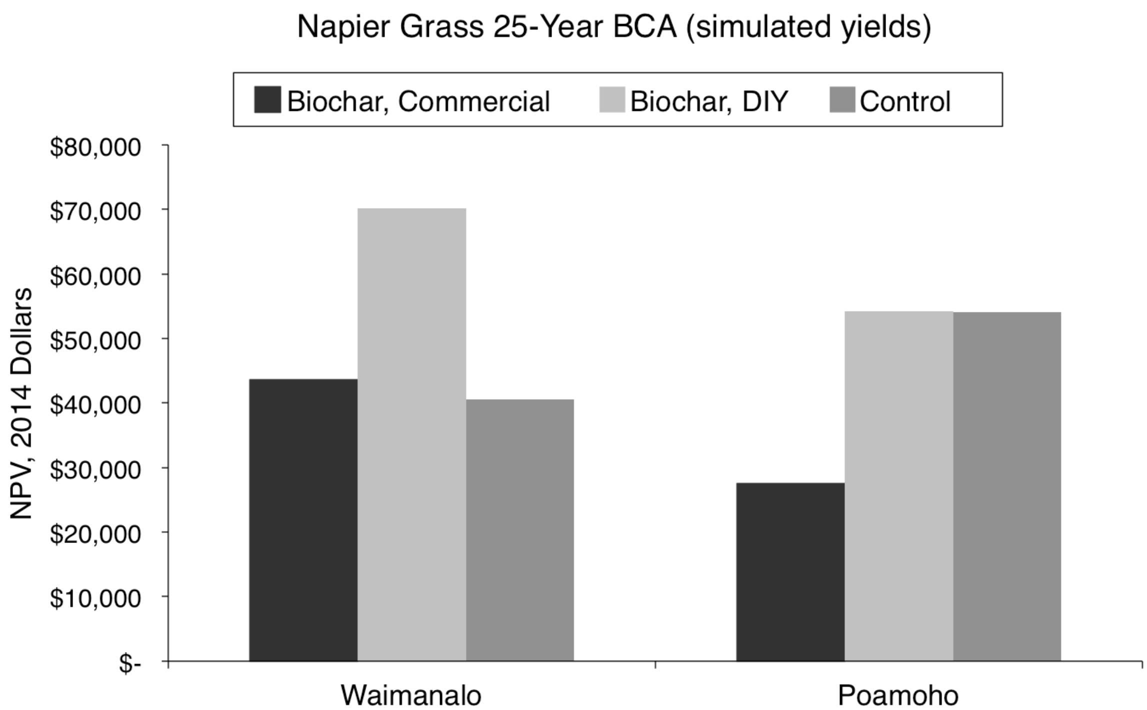

Figure 6.13. Napier grass production BCA, low GWP valuation scenario and adjusted yields.

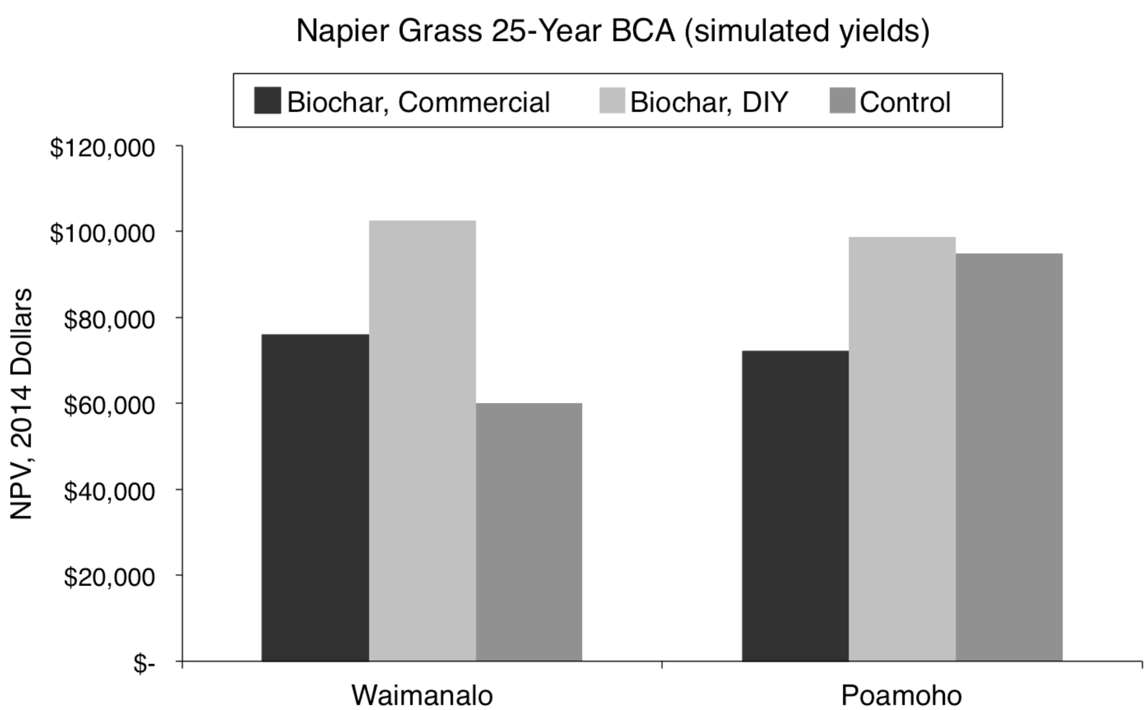

Figure 6.14. Napier grass production BCA, high GWP valuation scenario and adjusted yields.

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