# Carbon Sequestration Pilot Project Feasibility Study

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# Acknowledgements

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# Executive Summary

This work was completed for Boulder County, Colorado and the City of Boulder, Colorado as the main product in phase I of their joint carbon sequestration pilot project. The goal of this study was to "…undertake a pilot project to determine the feasibility of sequestering additional carbon in soils in agriculture fields, forests, grasslands/rangelands, and urban/residential properties." The project is intended to assess the potential for utilizing compost as a soil amendment, along with other agricultural practices, to sequester carbon in soil and vegetation and reduce greenhouse gas (GHG) emissions.

To achieve the project goals, Colorado State University (CSU) undertook this feasibility analysis of different management practices that could sequester carbon in soils and reduce greenhouse gas emissions to support the City of Boulder's and Boulder County's commitments to reduce greenhouse gas emissions. We evaluated eight agricultural practices, settling on five that could be feasibly applied in varying degrees on irrigated cropland, irrigated grass hay/pasture lands, and non-irrigated grazing lands (native grasslands and degraded rangeland) owned by Boulder County and the City of Boulder. For multiple reasons related to other city and county policies, an emphasis is placed on using compost as a soil amendment on agricultural lands while linking compost production to organic waste diversion from landfills and the associated greenhouse gas reduction benefits from that practice. Recycling organic matter as compost into agricultural soils has been shown to reduce greenhouse gas emissions by reducing the need for manufactured fertilizers while improving crop production and soil health. Assessing the feasibility of these practices involved the following methods:

- To help understand the types, quantities, and current fates of woody material in the county, Boulder County and City of Boulder staff organized a workshop with mountain forest and urban/suburban forest managers from Boulder County, the City of Boulder, the Natural Resource Conservation Service (NRCS), the State of Colorado, and the U.S. Forest Service.
- To help understand potential uptake and barriers to carbon farming practices, Boulder County and City of Boulder staff organized a feedback session with farmers and ranchers leasing Boulder County and City of Boulder lands.
- Farmers, ranchers, forest managers, and suburban/urban tree managers filled out surveys at the workshops (17), feedback sessions (5), and after the workshops and feedback sessions (3).
- CSU staff conducted telephone interviews (13) with Boulder County and City of Boulder producers, crop consultants, composting facility operators, livestock consultants, and dairy operators on the Front Range.
- CSU staff conducted a literature review of GHG mitigation benefits, life cycle analyses, and economic costs/benefits associated with the practices.
- CSU staff engaged in extensive consultation with interested parties in meetings, telephone calls, and emails with local and national experts in this field of study.

Optimizing the benefits of GHG mitigation in agricultural systems is best achieved through a systems-based approach, integrating the municipal and industrial processes with agricultural systems. The agricultural practices that appear most feasible to include in a carbon farming system in Boulder County follow:

- Applying compost as a soil amendment to cropland, grass hay/pasture, and degraded rangelands, where practical, and where applying compost doesn't exacerbate risks from invasive plants or where it may erode after application off of slopes into waterways.
- Add woody plant windbreaks (field buffers) and riparian buffers wherever practical to protect crops from dessicating winds, store carbon from the atmosphere, and provide wildlife and pollinator habitat.
- Convert to reduced-tillage and strip-tillage or no-tillage systems.
- Integrate cover crops into crop rotations.
- Use nitrification inhibitors or slow-release fertilizers.

Utilizing compost and cover crops to the maximum extent possible replaces some or all of the need for synthetic fertilizers, depending upon the crop.

Besides agricultural practices, CSU analyzed associated municipal and industrial processes that are linked to the compost production process. The following associated changes emerged as the most important drivers of greenhouse gas reductions:

- Diverting compostable wastes from landfills and producing and utilizing compost, and thereby recycling valuable crop nutrients and organic material back into soils to improve soil health, raise crop yields, raise the capacity of soils to hold rainfall/snowmelt/irrigation water, and sequester soil carbon.
- Diverting manure that would otherwise not be utilized as an agricultural amendment, is over-utilized, or is deposited into landfills or lagoons into the compost production process.
- Diverting into the compost production process any class A biosolids from wastewater treatment plants that are currently applied to rangelands outside the county or deposited into landfills, where the materials present no risk to public health or environmental degradation through pathogens or metals contamination.

All of the above practices have the potential co-benefits of avoiding methane emissions from landfills and/or manure lagoons, and of reducing water quality risks associated with nitrogen and phosphorus leaching/runoff.

All measures of carbon sequestration and greenhouse gas reductions are expressed in this study as carbon dioxide equivalents ($CO_2e$). The standard international unit for assessing GHG benefits from land use is metric tonnes per hectare, or Megagrams (Mg) per hectare. One metric tonne per hectare equals about 0.45 short (or “English”) tons per acre. A metric tonne is equal to about 1.1 short (“English”) tons, and one hectare is equal to about 2.5 acres. Global warming potentials recommended by the IPCC fifth assessment (IPCC 2014) calculate for 100-year time horizons were used, as follows:

- One metric tonne or short ton of carbon dioxide ($CO_2$) is equal to 1 metric tonne or short ton of carbon dioxide equivalents.
- One metric tonne or short ton of nitrous oxide ($N_2O$) is equal to 265 metric tonnes or short tons of carbon dioxide equivalents.
- One metric tonne or short ton of methane ($CH_4$) is equal to 34 metric tonne or short ton of carbon dioxide equivalents.

Readers of this report should note that methane is a relatively shorter-lived climate pollutant compared with carbon dioxide, and that the global warming potential of methane calculated over a 20-year time horizon is 86, or 2.5X greater than that calculated over a 100-year time horizon. Both the avoided methane emissions and the methane emissions from compost production would have a larger impact on the life cycle analyses presented in this study. The net effect of this difference is that the net benefits of both diverting organic waste from landfills, and diverting livestock manure from lagoons, into the compost stream (discussed below) are much greater if considered on a 20-year time horizon.

The technical potential of these practices, if combined as a system and implemented to the maximum extent possible on all county-owned and city-owned lands, as well as lands where conservation easements are held, is more than 100,000 metric tonnes (110,000 short tons) of net $CO_2e$ reductions per year. If extended to all agricultural lands within the county, the technical potential is more than 170,000 metric tonnes (187,000 short tons) of net $CO_2e$ reductions per year.

The economic costs/benefits of the practices range from a \$58 cost savings per acre (tillage reduction) to a \$235 additional cost per acre (applying compost), if no NRCS Environmental Quality Incentives Program (EQIP) savings are leveraged. If NRCS EQIP savings can be leveraged for the systems, the cost/benefits range from a \$73 cost savings per acre (tillage reduction) to a \$58/acre cost (planting windbreaks). Applying compost is currently not eligible for EQIP funding. The financial costs per metric tonne of GHG reduction range from a net savings (\$-200/metric tonne $CO_2e$ reduction for tillage reduction, \$-180 for adding cover crops if EQIP savings are leveraged) to a net zero cost (planting windbreaks and riparian buffers) to \$73/metric tonne $CO_2e$ reduction for compost additions on cropland.

The practices described apply equally to conventional and organic growers, with the exception of slow-release fertilizers or nitrification inhibitors as they are synthetic fertilizer products. Differences in conventional and organic production techniques will likely drive the relative applicability of the other practices. Compost and/or manure use and cover crops are widespread in organic systems, whereas tillage reduction is not. Boulder County reported that approximately 15% of producers on Boulder County lands were either in or were transitioning to organic systems by 2016 (Boulder County 2016).

These practices also extend equally to homeowners and landscapers. Substituting compost for synthetic fertilizers on lawns will lead to carbon sequestration benefits. Replacing synthetic fertilizers with slow-release fertilizers or utilizing nitrification inhibitors will reduce nitrous oxide emissions. Reducing and/or eliminating tillage and integrating cover crops into home gardens will lead to higher soil carbon sequestration. Planting trees in homes and municipal and industrial campuses will lead to net carbon sequestration in woody biomass where they meet landscaping needs and do not shade rooftop solar or solar gardens.

We recommend the following actions for Phase II of this project:

- Implement a five-year, small-scale compost-on-rangeland study to assess carbon sequestration and changes in plant communities in response to a compost application on degraded rangeland.
- Implement farm-scale, producer-based field trials for five years, as follows:
    - Irrigated Cropland: Utilize compost amendment, tillage reduction, use of slow-release fertilizers/nitrification inhibitors, cover crops, planting windbreaks on 2 sprinkler-irrigated cropland fields ranging 20-80 acres in size. We estimate the initial financial cost for implementing these practices is approximately \$6.8k (with EQIP) to \$12.4k (without EQIP) in the first year on a 20-acre field, and approximately \$5k-\$9k per year in following years for the first decade. Costs are likely to decrease after the 1st decade as soil health improves, the need for crop inputs drops, and yields increase. NRCS funds conservation practices under EQIP for 3-5 years, depending on the practice, to aid in practice adoption.
    - Irrigated grass hay/pasture: Utilize compost amendments, use of slow-release fertilizers/nitrification, and windbreaks on 2 sprinkler-irrigated grass hay/pasture fields ranging 20-80 acres in size. We estimate the initial cost for implementing these practices is approximately \$6.7k (with EQIP) to \$12k (without EQIP) per year on a 20-acre field, and approximately \$4.7k-\$11.4k in following years for the first decade. Costs are likely to decrease after the 1st decade as soil health improves, the need for crop inputs drops, and yields increase. NRCS funds conservation practices under EQIP for 3-5 years, depending on the practice, to aid in practice adoption.
- Conduct Additional Studies:
    - A five-year monitoring of vegetation and crop yield response along with documenting lessons-learned about carbon farming integration in the producer-based field trials described above.
    - An update to Matthew Cotton's organic materials study (Integrated Waste Management Consulting, LLC, 2014), adding the following:
        - Comprehensive analysis of potential methods to reduce the price of compost, including addressing policy barriers, management of the compostable materials stream, reducing shipping costs, addressing economic externalities, and other factors.
        - Analysis of site location possibilities based on available organic material streams identified in this report.
        - Reviewing possible sites for mid-scale, distributed compost generation with key community partners while examining on-farm compost production, aligning policy rules to realign the marketplace, market economics and the potential to utilize the livestock manure and biosolids waste stream generated within the county.

# Introduction

This analysis was prepared for Boulder County and the City of Boulder, Colorado, as part of the Carbon Sequestration Pilot Program, Phase 1 study. The overall project goal, as described in the phase 1 Request For Quotation, is as follows:

"…undertake a pilot project to determine the feasibility of sequestering additional carbon in soils in agriculture fields, forests, grasslands/rangelands, and urban/residential properties."

The project is intended to assess the potential for utilizing compost as a soil amendment, along with other agricultural practices, to sequester carbon in soil and vegetation and reduce GHG emissions. Sequestering carbon in agriculture requires a system-based approach, evaluating both carbon sequestration potential as well as emissions from associated trace gases like nitrous oxide or methane. Practices that increase sequestered carbon in soil or woody systems, if not designed carefully, can increase trace gas emissions, degrading the net carbon sequestration or even leading to net higher overall emissions. Because of the synergism between sequestering carbon and the potential for trace gas emissions, this study examines the net system greenhouse gas reduction benefits of a combination of conservation practices.

To achieve the project goals, CSU proposed to first undertake a feasibility analysis of different management practices that could achieve GHG management goals, and prepare a carbon farming plan based on the results of that analysis.

Under the Feasibility Study, we assessed the following:

1) What feedstock materials might be available for economically producing compost for use on Boulder County to apply to rangeland and cropland?
2) What is the net GHG balance associated with utilizing those materials? Does it matter where the compost is produced, from the perspective of net GHG emissions or net cost?
3) How much compost supply might reasonably be produced from materials within the county, and how much compost is being produced near Boulder County that might be utilized on county and city lands?
4) In addition to utilizing compost in agricultural operations, which additional agricultural practices that can reduce and/or offset GHG emissions are most feasible on lands owned and managed by Boulder County and the City of Boulder?

We evaluated potential compost feedstocks from the following sources:

- Compostable waste that might be diverted from landfills into compost production
- Wood from fire mitigation and habitat restoration efforts on Boulder County Lands
- Wood from similar work on state and federal forests
- Wood from ash trees that may be available due to the emerald ash borer infestation
- Manure from livestock, both within (horses) and outside (dairy and beef cattle) Boulder County
- Class A biosolids produced from waste water treatment plants within Boulder County

## Definitions

All measures of carbon sequestration and greenhouse gas reductions are expressed in this study as carbon dioxide equivalents ($CO_2e$). The standard international unit for assessing GHG benefits from land use is metric tonnes per hectare, or Megagrams (Mg) per hectare. One metric tonne per hectare equals about 0.45 short (or "English") tons per acre. A metric tonne is equal to about 1.1 short ("English") tons, and one hectare is equal to about 2.5 acres. Global warming potentials recommended by the IPCC fifth assessment (IPCC 2014) calculate for 100-year time horizons were used, as follows:

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Readers of this report should note that methane is a relatively shorter-lived climate pollutant compared with carbon dioxide. The global warming potential (GWP) of methane calculated over a 20-year time horizon is 86, or 2.5X greater than the GWP calculated for a 100-year time horizon. Avoided landfill/lagoon methane emissions and the methane emissions from compost production would have a larger impact on this study's life cycle analyses. The net benefits of utilizing compost are even greater if considered on a 20-year time horizon.

## Potential GHG Mitigation Practices Considered in this Study

We analyzed agricultural practices shown to sequester carbon in soils and trees, and reduce trace gas emissions of the GHGs nitrous oxide, methane, and carbon monoxide. There are several good summaries that explain how agricultural practices can remove carbon from the atmosphere and store it in soils and trees, and/or reduce trace gas emissions from agriculture. For those looking for a comprehensive summary on the topic, here are three documents that provide details:

- ***Agriculture's Role in Greenhouse Gas Mitigation***, by Keith Paustian, John Antle, John Sheehan and Eldor Paul. Published by the Pew Charitable Trust. 2006. http://www.pewtrusts.org/~/media/legacy/uploadedfiles/wwwpewtrustsorg/reports/global_warming/pcgccghg092006pdf.pdf
- ***Agriculture's Role in Greenhouse Gas Emissions and Capture.*** Greenhouse Gas Working Group Rep. ASA, CSSA, and SSSA, Madison, WI. 2010. https://www.soils.org/files/science-policy/ghg-report-august-2010.pdf
- ***Climate-Smart Soils***, by Keith Paustian, Johannes Lehmann, Stephen Ogle, David Reay, G. Philip Robertson, and Pete Smith. Nature 532:49-57 2016. https://www.nature.com/nature/journal/v532/n7597/pdf/nature17174.pdf

Following is a summary of different agricultural practices we analyzed for Boulder County, with a brief explanation of their GHG mitigation benefits:

- Apply Compost to Rangelands and Croplands: Applying compost to agricultural soils, whether it is applied to the surface or tilled into the soils upper layers, has three major GHG benefits:
  - By diverting organic waste from landfills and converting it into compost we avoid the climate-warming methane emissions that occur when waste like food and yard waste are buried in landfills.
  - Adding compost to degraded rangeland and cropland improves soil fertility and leads to higher soil carbon stocks.
  - Farmers and ranchers can reduce the use of synthetic fertilizers when compost is applied, and therefore the emissions associated with manufacturing those fertilizers (a very high-energy process) can be avoided.
- Slow-Release Fertilizers and Nitrification Inhibitors: Using these products helps farmers and ranchers reduce emissions from nitrous oxide, a very powerful global-warming trace gas that can emit in high quantities when synthetic fertilizer is applied to crops and pasture.
- Cover Crops: By planting cover crops in the fall and overwintering them to grow in the spring, farmers add additional organic matter to soils, through additional net photosynthesis in the crop rotation, reduce the need for synthetic fertilizers, and improve soil fertility, leading to soil carbon sequestration.
- Reduce Tillage or convert to No-Tillage or Strip-Tillage**:** Reducing tillage or growing crops without tillage leads to higher soil organic matter and improves soil health and soil fertility, leading to soil carbon sequestration.
- Add Windbreaks (Field Buffers) and Restore Riparian Buffers: Trees and shrubs in windbreaks sequester carbon in their trunks, branches, and roots, reduce erosion and enable higher crop yields in fields downwind, which can lead to higher soil organic matter and soil carbon sequestration. Like in windbreaks, trees and shrubs restored in degraded riparian areas sequester carbon in their trunks, branches, and roots, reduce erosion, and build organic matter in soils, leading to soil carbon sequestration.
- Integrating Livestock into Cropping Systems: Bringing in livestock to graze cover crops in the spring prior to planting row crops or grazing crop residues in the fall can increase soil organic matter through the livestock

manure, while making more of the plant residue nutrients available for plant growth, leading to soil carbon sequestration.

- Apply Biochar to Rangelands and Croplands: Biochar, which is a form charcoal produced from organic material through pyrolysis, can sequester carbon in soils. When applied at high rates, it has been shown to reduce trace gas emissions like nitrous oxide. Agronomic studies indicate biochar can increase crop yields under some conditions, leading to higher organic matter in soils. Some life cycle analyses indicate that the use of biochar can lead to net carbon sequestration in soils.

## Benefits of Utilizing Compost

Compost is a valuable commodity in the agricultural community and in home gardening and landscaping. When applied to soil, it enhances water holding capacity, provides stable, slow-release nutrients, enhances soil carbon sequestration and increases plant production and crop yields. Within the whole farm carbon farming framework, compost application can be a valuable part of a smart, comprehensive plan to manage carbon in our agricultural systems. In a rangeland setting it is best to identify sites most appropriate for compost application with a land manager and conduct application alongside a holistic or managed grazing regime.

The benefits of utilizing compost in agriculture and landscaping extend beyond the direct improvements to soil health. Composting has been described as "Recycling's Final Frontier" (Levitan 2013). Between 30 and 40% of the food produced in the U.S. is never consumed, and most of the waste ends up in landfills. Besides food waste, a great deal of other organic (and compostable) material such as yard waste, construction waste, and wood from urban/suburban tree management ends up in landfills. Organic waste in landfills is subjected to an oxygen-depleted environment, where it decomposes into methane, a powerful greenhouse gas. The U.S. EPA estimated in 2014 (the most recent year where data were available) that landfill methane in the United States comprises approximately 2.5% of the total GHG emissions (U.S. EPA 2017b). By diverting food waste, yard waste, and other compostable materials into composting operations, one can recycle the plant nutrients (nitrogen, phosphorus, potassium, and other nutrients) present in that waste back into the food production cycle. This avoids the need to manufacture these nutrients into synthetic fertilizers, which is a very energy-intensive process resulting in significant GHG emissions. Additionally, recycling the organic material present in diverted landfill waste into compost and applying it to soils as compost improves soil health, raises soil organic matter levels, improves crop yields, and raises soils' capacity to hold rainfall, snowmelt, and irrigation water.

Certain organic waste products (like mulch or raw manure) are often incorrectly called compost. Compost can be made from anything that was once alive, but is not the "raw" material itself. Unlike mulch or manure, compost it is the final product of a managed thermophilic process through which microorganisms break down organic materials into stable organic matter and reduce or eliminate the pathogen population before applying it to the soil. A well-managed composting process has plenty of oxygen, goes through a high heat phase which accelerates the microbial biodegradation of organic materials and disease organisms, and produces a stable form of organic matter consisting of carbon, nitrogen, and a host of other plant nutrients. Well-made compost is free of weed seeds and harmful pathogens. For environmental and agronomic reasons, it is important to note that the type of nitrogen found in compost (organic N) is not the same as the nitrogen in synthetic fertilizers (inorganic N).

Compost production and application offers an opportunity to decrease GHG emissions, promote soil carbon sequestration, and increase resilience in natural and working lands. A life cycle approach best illustrates the GHG benefits of using compost in agriculture and landscaping since one can then examine the typical fate of (and GHG emissions from) the raw materials used to make compost. Utilizing waste materials has the greatest GHG benefit since one avoids other GHG emissions by doing so. In contrast, one should avoid creating compost in a way that leads to higher GHG emissions. For example, harvesting unusable crop residues, or harvesting a stable and thriving forest, in order to compost the material and return it to an agricultural field, is likely to lead to overall net GHG emissions. Using waste products such as diverted landfill waste, urban wood waste from construction or landscaping, woody biomass from forest health and fire mitigation projects, or livestock manure diverted from manure lagoons is likely to have a net overall reduction in GHG emissions when examined on a life cycle basis.

# Methods

We gathered information from forest managers, farmers, ranchers, and compost producers in and near Boulder County through the following means:

- To help understand the types, quantities, and current fates of woody material in the county, Boulder County and City of Boulder staff organized a workshop with mountain forest and urban/suburban forest managers from Boulder County, the City of Boulder, the Natural Resource Conservation Service (NRCS), the State of Colorado, and the U.S. Forest Service.
- To help understand potential uptake and barriers to carbon farming practices, Boulder County and City of Boulder staff organized a feedback session with farmers and ranchers leasing Boulder County and City of Boulder lands.
- Farmers, ranchers, forest managers, and suburban/urban tree managers filled out surveys at the workshops (17), feedback sessions (5), and after the workshops and feedback sessions (3).
- CSU staff conducted telephone interviews (13) with Boulder County and City of Boulder producers, crop consultants, composting facility operators, livestock consultants, and dairy operators on the Front Range.
- CSU staff conducted a literature review of GHG mitigation benefits, life cycle analyses, and economic costs/benefits associated with the practices.
- CSU staff engaged in extensive consultation with interested parties in meetings, telephone calls, and emails with local and national experts in this field of study.
- The carbon sequestration and greenhouse gas benefits of different practices were derived from the previous study for Boulder County Parks and Open Space by Easter *et al*. (2014).

In addition to the surveys and interviews, we gathered other information through a literature search and discussions with colleagues and agricultural professionals. We had extensive, critical support from the following people:

- Calla Rose Ostrander, independent contractor
- Jeffrey Creque, Carbon Cycle Institute
- Dan Matsch, Ecocyle
- Tracy Kessner, Intern at Ecocycle and graduate student at the University of Colorado

# Findings and Results

## Compost Feedstock Materials Analysis

Following are key findings from research into potential feedstocks for producing compost. There appears to be a firm annual source of compostable materials to produce approximately 25,000 short tons of compost from Boulder County compost feedstock per year (diverted landfill waste plus wood waste from urban/suburban tree management), with additional sources that could double or triple that amount if it could be economically utilized (biosolids, manure from nearby dairies, horse manure, wood chips from forest management and urban/suburban tree management).

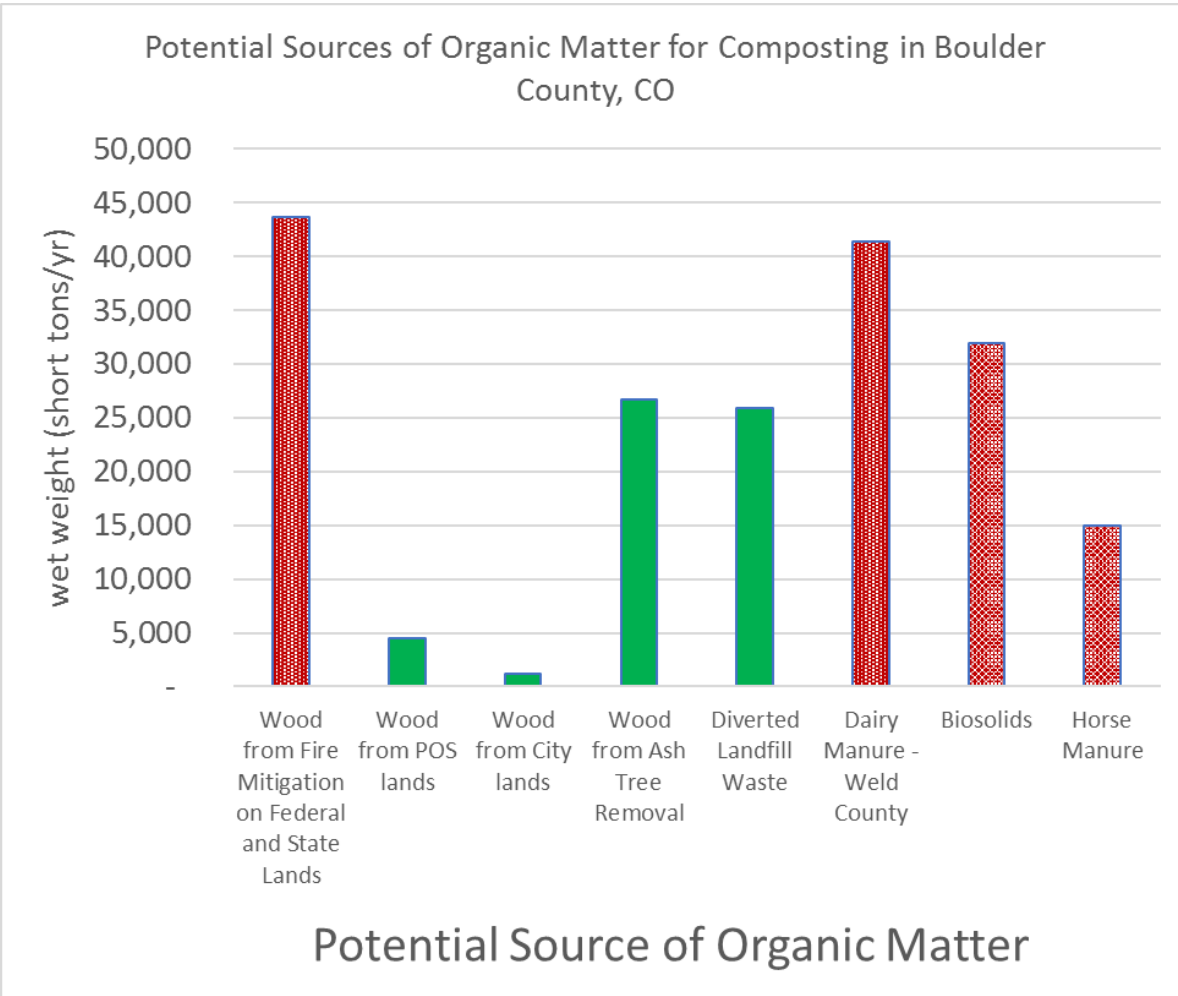


*Figure 1. Yearly potential sources of organic matter for composting in Boulder County, Colorado. Green solid bars indicate a predicted firm supply, red crosshatched bars indicate less firm supply or materials where additional data are needed.*

## Woody Material

- Boulder County Parks and Open Space Lands (BCPOS): An average of 4,004 short tons per year of woody material is harvested, ground on site, and hauled from BCPOS lands. The majority is hauled to be burned in heating boilers at the BCPOS and Boulder County Jail building. The portion of the material that is not burned is used for landscaping or hauled to the A-1 organics site for use in composting.
- City of Boulder Mountain Parks: An average of 876 short tons per year of woody material is harvested and hauled to sorting yards where it is utilized by community members as fuel for heating homes.
- Federal and State Forest Lands: Little to no material is currently being hauled off of USFS lands during fuels reduction treatments at the present time. Approximately 2,000 acres are treated on the Front Range, and approximately 20 short tons/acre are felled, piled and burned on site, totaling approximately 40,000 short tons.

- A very small but un-measured amount of furniture-grade hardwoods are harvested in Boulder and Longmont and processed locally for handmade furniture. This material has a significant carbon sequestration benefit, however the amount was considered to be insignificant compared to the larger volume of material destined for other uses.
- There are no estimates of woody biomass currently processed from the urban and suburban areas of Boulder County (called "trees outside of forests"). Based on conversations with local officials, we estimated a total of 10 short tons of such material are processed daily in Boulder County, and we apportioned the materials to the populations of Boulder, Longmont, and Lafayette/Louisville/Superior based on population weighting. This totals approximately 3,650 short tons/year.
- The majority of ground and/or chipped woody material is hauled to the A-1 organics compost production site in Keenesburg, CO. A small but unquantified portion is used locally for mulch and landscaping material.
- Chipped and/or ground wood has occasionally been collected in Boulder County by wood pellet manufacturers and trucked to factories on the Western Slope. Likewise, whole harvested logs are occasionally gathered and trucked to lumber mills or construction log processing facilities in Northern Colorado and the Western Slope.

### Food and Yard Waste

- A waste diversion study prepared by Cotton (2014) for Boulder County predicted that approximately 92,000 short tons of organic waste (food and yard waste, other compostables) are generated annually in the county. The study predicted that approximately 25,829 short tons of that total might be realistically recoverable through organic waste diversion programs in the future. Approximately 13,000 short tons (about half of what the Cotton study predicted to be recoverable) are currently being diverted from landfills as of 2016, but this figure is expected to rise since the city of Longmont recently began its organic waste collection program. This waste appears to currently be hauled to the A-1 organics composting facility in Keenesburg, CO.

### Livestock Manure

- The National Ag Statistics Service (NASS Quickstats) estimates that Boulder County is home to more than 15,000 horses, including a large number over-wintered here on the front range but used in the Colorado high country during the summer. This number of horses produces approximately 135,000 short tons of manure annually (IPCC 2006). If stabled, this number of horses produces about 180,000 short tons of combined manure + stall waste each year (IPCC 2006). Several horse stable businesses collect and haul their manure and stall waste either to landfills or to composting operations outside of the county. The opportunity exists to divert that manure from landfills and into local composting operations. We were not able to determine the potential amount of manure that could be diverted into composting operations, or how much horse manure and/or stall waste is already being composted. A number of stabling operations are already composting their waste and applying it to pastures, or hauling their waste to composting operations, though the total amount of manure/stall waste being composted could not be quantified at this time. We did calculate a scenario for discussion's sake, assuming one-third of those horses are stabled and approximately a quarter of the stall waste from those horses is not currently composted, is economically recoverable, and could be composted. This is a large potential source of high quality, compostable solids, and investing in policies, collection systems, and technologies to utilize this resource could significantly increase the amount of compostable feedstock available within the county, and further study is warranted.
- Numerous dairies and beef feeding operations exist within 40 miles of Boulder County. We examined the potential to collect manure from six dairies located within 13-27 miles of the undeveloped portions of eastern Boulder County where a hypothetical composting facility might be sited or to which composted manure could be hauled to apply to cropland and degraded rangelands. All of these dairies are currently separating a portion of the manure and either composting it on site or applying it directly to soils used to grow forage for dairy cattle. The approximate efficiency of the existing separators is 40-50%. Approximately half of the manure solids generated by the dairies is stored in anaerobic lagoons and is a major source of manure methane.
- A potential source of manure solids for composting may be to invest in improving manure management at the dairies to divert a larger quantity of manure solids from the lagoons, and either compost the material on site for use in Boulder County, or ship the manure solids to a composting facility in Boulder County. Assuming the manure separation efficiency might increase from 45% to 75%, based on state-of-the-art separator technology (installing screw separators integrated with centrifuges), this would produce approximately 39,400 tons of

additional compostable material per year, assuming each dairy has 1,500 cattle, based on phone interviews to several of the dairies.

### Biosolids

- Biosolids are the organic material processed at waste water treatment plants (WWTP). Biosolids are commonly used in making compost, are applied directly to grazing land and cropland, or are buried in landfills. The State of Colorado regulates how biosolids must be treated to eliminate disease transmission risk before it may be applied to soils or used in making compost (Colorado Department of Public Health and Environment 2018). Biosolids exceeding threshold levels for pathogens, toxins, heavy metals or other potential contaminants are prohibited from being used in compost production and cannot be applied to soils.
- Class A biosolids (those deemed safe under state regulations) represent an additional potential source for compost production. The biological and chemical composition of biosolids are similar to that of partially-composted livestock manure, though a significant amount of nitrogen, phosphorus, and other plant nutrients are not organically bound. Research indicates these free, more soluble nutrients affect soil ecosystems differently from finished compost when applied to soils (Bowles *et al.* 2015). Unbound nitrate is more water soluble and more mobile, and ammonium is more likely to volatize, compared with organically-bound nitrogen. Biosolids are commonly combined with other organic material feedstocks as inputs into the compost stream in other U.S. locations (USDOE 2017, USEPA 2017, Brown and Leonard 2004). Soils respond differently to fresh biosolids compared with fully-composted biosolids (e.g. thermophilic-processed and aged) in that nutrients are not stabilized and can more readily leach and volatilize from fresh biosolids compared with fully-composted materials. At least a dozen WWTP facilities in Boulder County produce biosolids (Information from the State of Colorado, compiled by T. Kessner, personal communication). The majority land-apply the biosolids outside Boulder County on rangeland, pasture and/or cropland at locations not identified as part of this study. Some biosolids generated in Boulder County may already be part of the composting stream, as indicated by local compost suppliers. Compost producers serving Boulder County use biosolids as a source material in several products (A-1 Organics, Western Disposal).

For approximately the next decade, a firm supply of approximately 54,000 short tons of firm supply of organic matter produced within the county could be available for composting, yielding approximately 27,000 short tons of compost per year derived from sources of organic material within Boulder County. This assumes 50% of the mass of raw materials is lost to water evaporation and decomposition in the composting process (A-1 Organics, personal communication, and D. Matsch, personal communication) (Figure 1). This would be largely from diverted landfill waste (~26,000 short tons/year), wood from ash tree removal (~25,000 short tons/year), and other sources of wood (~4,000 short tons/year). At the suggested application rates, there could be enough compost generated from local materials to treat about 2,800-3,000 acres of irrigated cropland and/or grass hay/pasture land in Boulder County, or nearly all of the non-irrigated grazing land (rangeland) in the county that could reasonably be treated. This is based on average land application rate of 9.3 short tons of compost per acre per year to irrigated cropland or hay/pasture systems, or 8 short tons per acre applied once every five years to grazed, non-irrigated grasslands (rangeland). Amending agricultural soils at more moderate rates (~4.5 tons/acre/yr to irrigated cropland, ~4 tons/acre/yr to irrigated grass hay/pasture, ~4 tons every 5 years to degraded rangeland) would extend the amount of compost generated from materials sourced within the county to about 5,600-6,000 acres per year. Reducing compost application rates to treat larger areas would likely yield similar overall GHG reduction benefits per ton of total compost applied, as the benefits of compost application within agronomically-recommended rates tends to scale directly with the application rate (Paustian Group, unpublished data).

*Table 1. Cropland and Rangeland totals in Boulder County. Sources of data: Boulder County (2016), City of Boulder (2017), USDA Cropscape (2018). Please note that degraded rangelands are the most likely rangeland class to receive compost amendments, and are a subset of the rangeland total shown below. Lands listed below as "Boulder County" include lands where either the title or a conservation easement is owned by the county.*

| Ownership | Irrigated Cropland | Irrigated Grass Hay/Pasture | Rangeland |
|---|---|---|---|
| City of Boulder | 202 ha / 500 acres | 2024 ha / 4,998 acres | 4,049 ha / 10,000 acres |
| Boulder County | 7,393 ha / 18,261 acres | 4,942 ha / 12,207 acres | 3,294 ha / 7,368 acres |
| Privately owned | 8,351 ha / 20,627 acres | 1,450 ha / 3,582 acres | 12,548 ha / 6,230 acres |
| Total | 13,664 ha / 33,751 acres | 8,416 ha / 20,786 acres | 19,890 ha / 49,150 acres |

In the short term and without significant policy change and changes in organic waste diversion rates or utilization of other sources, there likely will be enough compost generated within the county to amend lands in the following scenarios:

- up to about 17% of irrigated cropland and irrigated grass/hay lands owned by the city and county.
- all of the county-owned rangelands that would be suitable for compost amendment and 14% of the irrigated cropland and grass/hay lands.

The amount of compost could potentially increase depending upon the economic availability of biosolids, horse manure, dairy manure from adjoining counties, and other wood supplies from fire mitigation and forest habitat restoration efforts.

The long-term scenario is more speculative. We developed the following scenario wherein all potential organic materials generated within the county that are currently not used for other purposes could be diverted into compost production. This includes the following:

- Diverted landfill waste (~13,000-26,000 short tons/yr)
- Wood from urban/suburban tree management, including ash trees (~18,000-36,000 short tons/yr)
- Additional manure diverted from dairy lagoons in western Weld County (~42,000 short tons/yr)
- Additional class A biosolids from waste water treatment plants that are suitable and safe for composting (~32,000 short tons/yr)
- Horse manure from within Boulder County (~15,000-90,000 short tons/yr)
- Wood from fire mitigation and habitat restoration on state and federal forest lands (~40,000 short tons/yr)

The sum of these feed stocks totals 160,000-266,000 short tons of compostable feed stock per year, which could potentially be used to produce 80,000-133,000 short tons of compost per year. This amount of material could be amended to about 10,000-16,000 acres of cropland each year at high application rates (~9 tons/acre/yr to irrigated cropland, ~8 tons/acre/yr to irrigated grass hay/pasture, ~8 tons/acre every 5 years to degraded rangeland), or 20,000-32,000 acres of cropland at moderate application rates (~4.5 tons/acre/yr to irrigated cropland, ~4 tons/acre/yr to irrigated grass hay/pasture, ~4 tons every 5 years to degraded rangeland).

Such a concerted effort to utilize compostable resources could lead to a supply of compost adequate to amend approximately 53-86% of the city and county irrigated cropland, grass hay/pasture land, and all of the degraded rangelands suitable for compost addition in Boulder County. Meeting 100% of the needs would require importing additional compost from nearby counties.

## Net Greenhouse Gas Balance of Compost Production

The only facility producing compost in large quantities serving Boulder County is A-1 Organics. Their composting yard is located in Keenesburg, CO, located 60, 45, and 44 miles from Boulder, Longmont and the Lafayette/Louisville/Superior centroid, respectively. Most of the currently composted organic materials generated in Boulder County appear to be hauled to Keenesburg for composting.

There are regulatory and policy barriers preventing small- to medium-sized composting sites from being sited in Boulder County. Current permitting systems drive compost production into large, centralized sites. The economics of composting along with odor issues associated with composting appear to have driven compost production into unincorporated areas outside of Boulder County, far from sources of compostable materials within Boulder County. Whereas this has a significant effect on the economics of composting and significantly raises the cost of producing and hauling compost to Boulder County, the hauling emissions contribute only 3-5% of the net GHG balance of compost production (Figure 2) when compared with producing compost from a facility or set of facilities located within Boulder County.

In our analysis, it is apparent that the greatest immediate GHG benefit from composting organic waste for application to agricultural soils is related to diverting organic waste from landfills and preventing landfill methane emissions (Figure 2). Diverting this waste accounts for approximately 8,000 metric tonnes of $CO_2e$ reduction benefits in Boulder County, which is about twice the magnitude of the emissions associated with hauling and the composting process. This is equivalent to offsetting the emissions from about 1,713 American automobiles each year (EPA 2018).

Livestock manure is a valuable and commonly-used feedstock material for producing compost. On the Colorado Front Range, the main sources of livestock manure for agricultural use are confined feeding operations for beef and dairy cattle. Because of the way the manure is stored, the GHG emissions from manure in beef confined feeding operations tend to be relatively low compared with confined feeding operation dairies, where manure is typically stored in lagoons where the solids decompose in an oxygen-free atmosphere to become a major source of methane. As is the case with using diverted landfill waste to produce compost, by composting dairy manure solids rather than storing it in lagoons, one can avoid significant GHG emissions. The right-most bar in Figure 2 shows the potential benefit of diverting additional dairy manure solids from lagoons by upgrading manure solids separation equipment or converting from lagoon storage to other storage methods. We present this as a potential additional opportunity to reduce net system GHG emissions. Working with regional dairies to divert solids from manure lagoons in exchange for use of the composted manure solids could be a cost-effective, long-term method to reduce agricultural GHG emissions and sequester soil carbon.

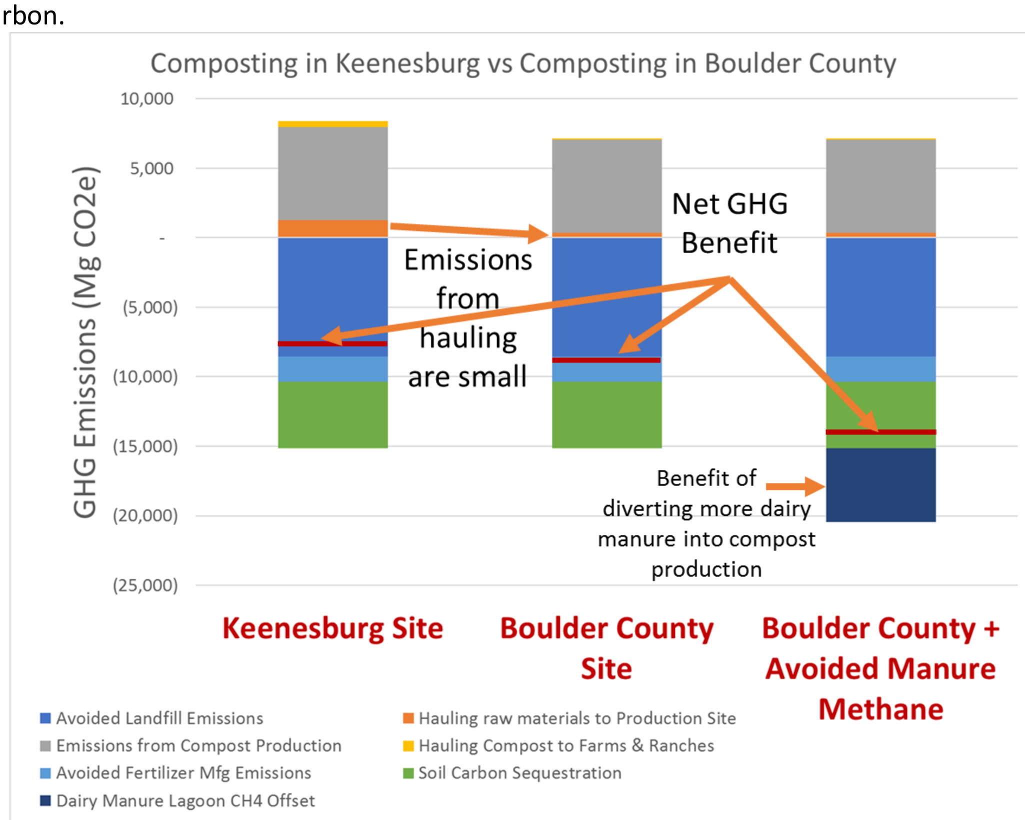


*Figure 2. Composting siting scenario analysis. The Keenesburg site scenario assumes compostable materials are hauled from Boulder County to Keenesburg for composting, and no additional livestock manure is diverted from anaerobic lagoons for composting. The Boulder County Site scenario assumes an investment in improving manure waste diversion efficiency from lagoons.*

# Feasibility of Potential Greenhouse Gas Mitigation Practices

## Results of Feasibility Survey

### *Applying Compost to Cropland, Pasture, and Rangelands*

All producers surveyed or interviewed had either produced their own compost from livestock manure, agricultural waste, or other materials and applied it to their cropland and pastures, or had purchased compost to apply to their lands. All expressed interest in continuing the practice but cited the cost of the material and the cost to haul as a major barrier at this time. All producers expressed concern about plastic contamination, consistency in characteristics, and having adequate plant-available nutrients to support crop yields. None of the producers interviewed either fertilized or applied compost to non-irrigated grazing land or rangeland. Site visits and telephone conversations with compost producers indicate that compost products with low contaminant levels are available, however plastic particle contamination is likely to be present in even some screened products into the near future until haulers and compost producers address the plastics contamination issue more effectively.

City of Boulder and Boulder County staff expressed concerns about the potential effects of compost amendments on plant communities in intact, native rangelands. Research documented in Blumenthal *et al*. 2017, Ippolito *et al*. 2010, and Ippolito *et al*. *2009* indicate that organic matter amendments can exacerbate issues with invasive weeds when effective weed management measures are not implemented. They recommended that compost amendment trials focus on degraded rangelands and that targeted weed management through grazing or other measures be implemented during the trials to achieve desired management objectives. Research by Ryals et al. (2016) indicates that targeted weed management in concert with compost amendments improves rangeland condition while addressing weed issues. Successful vegetation management with organic amendments will depend directly upon effective rangeland monitoring, grazing prescriptions, and collaboration between rangeland managers and ranchers.

### *Utilizing Slow-Release Fertilizers or Nitrification Inhibitors*

All producers surveyed or interviewed currently use slow-release fertilizers or nitrification inhibitors in  the majority of their fertilizer applications. The practice is utilized in early- and mid-season fertilization on fields where late-season irrigation water is not likely to be available, and growers are applying larger water quantities in the hopes of saturating the rooting zone for crops to utilize later in the growing season when irrigation water is no longer available. Utilizing slow-release fertilizers or nitrification inhibitors helps prevent nitrogen fertilizer from being leached or washed from the rooting zone during irrigation. No practice or cost barriers to the use of these products were expressed  by growers, whereas fertilizer distributors queried in the region indicated these products cost 10-20% more, depending on the product used, compared with simply using conventional fertilizers. Extending the practice to all growers for all crops may be a cost barrier for some growers.

### *Integrating Cover Crops into Crop Rotations*

All of the producers surveyed or interviewed expressed interest in utilizing cover crops, and 40% of growers had utilized them to some extent. Two major barriers were identified for integrating cover crops: 1) Cover crops are difficult to establish in the Front Range climate without sprinkler irrigation systems, and 2) late-season irrigation water is needed to reliably get a late-summer/early fall cover crop to germinate and establish. Cover crops can most easily be established after small grains and corn silage because of the timing of the harvest. It is possible to establish cover crops after grain corn, however if the grain is harvested much after mid-October it can be difficult to establish a cover crop before winter weather. Sugar beets are usually harvested too late in the season for a winter cover crop to be reliably established.

### *Reducing Tillage*

Reducing tillage in Boulder County is most practical on dryland cropping systems and sprinkler-irrigated cropland. Flood irrigation systems require bed preparation and minimizing obstructions to flowing water caused by crop residues. The majority of growers interviewed who had sprinkler irrigation systems on their cropland used no-till or strip-till systems on those lands to some degree. All of the growers indicated they would like to use no-till or strip-till systems. Growers identified the cost of no-till seeding equipment as a significant barrier to using no-till or strip-till systems widely. All of the growers indicated they may desire to periodically use heavy tillage to address soil compaction if it occurs.

### *Incorporating Livestock*

Approximately half of the growers indicated they periodically graze livestock on crop residues and/or hay fields after the harvest season. Growers unanimously agreed that reliable fencing is required for this practice and adding new fencing would be prohibitively expensive on unfenced fields and could be a complicating hazard for some cropland equipment operations.

### *Windbreaks, Shelterbelts and Riparian Buffers*

None of the producers surveyed or interviewed have planted agroforestry systems or woody crops. Two barriers were identified: 1) availability of irrigation water for establishing the trees, 2) producer's concerns about the shading and/or competition effects of tree rows, and complications for operating heavy equipment around trees. No cost barriers were identified for acquiring or establishing trees, however that could be because none of the growers had attempted the practice.

### *Biochar*

None of the producers surveyed or interviewed had applied biochar to soils, nor did they know anybody who had used biochar. All expressed interest in learning more but also expressed concern that the current price of biochar ($200-300/yard) is a barrier with commodity crop production.

There is significant interest from the Boulder County and City of Boulder in trying to utilize biochar as an agricultural amendment, and so we present the discussion and analysis that follows.

Recent research into the use of biochar has led to new agronomic recommendations for biochar's use on croplands and grasslands (Francesca Cotrufo, unpublished data, Biochar Now, personal communication, Cool Planet, personal communication). New, more cost-efficient practices have emerged, focusing on turf applications, high-value specialty crops, and to some degree, commodity crops (Ibid). Biochar use on golf courses has been shown to reduce water demand (Brockhoff 2010), and its use in specialty crops, fruit, and vegetable production has shown significant crop yield benefits in certain cases. The biochar product type and application rate varies significantly for each crop involved, and so the best use and application rate for specialty crops in Boulder County are best discussed directly with biochar manufacturers and crop advisors experienced with biochar use. The cost of biochar inputs relative to the value gained in crop production is a significant limitation in the current use of biochar in U.S. agriculture.

For commodity crops grown in Boulder County, the recommended practices by two manufacturers is to utilize a pelletized product to support crop establishment and production, applied in the seeding row in small to moderate quantities (50-400 lbs/acre) at the time of seeding. Costs for products used in this manner lists between $50-$350 per acre, though like with most agronomic products purchased in bulk, manufacturers may discount bulk purchases. Some manufacturers offer net profitability guarantees for their product when used in recommended quantities and methods and when an untreated control plot is planted for comparison purposes.

The net GHG life cycle benefits of biochar vary greatly with location, source material, manufacturing process, and application method. The total climate benefit depends significantly on the type of raw material used in the production process, what the GHG fate of that product would have been had it not been sourced for biochar, how the product is manufactured, and the hauling emissions associated with transporting raw materials to the manufacturing plant and then back to the field or pasture.

Life cycle analyses of biochar (Ericsson *et al.* 2017, Thornley *et al.* 2015, Lugato *et al.* 2013, Hammond *et al.* 2011, Ibarrola 2011) generally show a net GHG benefit, though not in all cases. At high application rates, biochar has been shown to reduce soil nitrous oxide emissions (Cayuela *et al.* 2014), however such application rates do not appear to be cost-effective for the commodity crops grown in Boulder County. The pyrolysis method used and the extent to which co-products (heat, electricity generation, liquid fuels) are utilized are major drivers in the overall life cycle benefit of using biochar. When no co-products are utilized in the biochar manufacturing process, the life cycle greenhouse gas benefit is small or indicates biochar is a net source of GHG emissions.

In a conversation with the owner of Biochar Now (www.biocharnow.com) (James Gaspard, personal communication) we learned that this Berthoud, CO company currently utilizes beetle kill pine harvested from Front Range forests, and has recently negotiated a sourcing agreement to divert organic landfill waste (tree limbs, untreated construction lumber) from the Larimer County Landfill. They have the capacity to accept ash trees (either whole or shredded to 6" or larger chunks) killed by the emerald ash borer in the range of 20,000 – 30,000 tons per year. The company is prepared to discuss arrangements to share in the hauling costs for material trucked from Boulder County. These sourcing arrangements would likely benefit the net GHG life cycle emissions of the product, since diverting landfill waste would avoid landfill methane emissions, and shortening the transportation distance for raw feedstocks would reduce transportation emissions.

Without an estimate of the emissions during the pyrolysis process, we cannot at this time produce a life cycle estimate for this product for Boulder County, though with the source material described it likely could lead to a net reduction in greenhouse gases combined with an agronomic benefit.

The other main manufacturer of biochar available in agronomic quantities is Cool Planet (www.coolplanet.com). Their CoolTerra product is manufactured in Louisiana, and the source material is variable, ranging from agricultural waste products shipped from overseas to agricultural residues and wood products harvested locally or regionally. A life cycle analysis of the cool planet product is underway at Colorado State University (Paustian, personal communication) but until that is completed we cannot estimate the net GHG life cycle benefits of the product for Boulder County, whereas research trials with the product have shown a net agronomic benefit (Cotrufo, unpublished data).

The current application rates recommended for biochar (50-400 lbs/acre) could lead to small to moderate net GHG benefits in cases where a life cycle analysis of the product indicates there is a net GHG benefit from the manufacturing process. For example, 300 lbs of biochar with 90% carbon content applied on an acre of soil could potentially have a net $CO_2e$ value of about 0.18 metric tonnes of $CO_2e$ benefit assuming 50% of the potential benefits are offset by the hauling and manufacturing process and 20% of the carbon decomposes while 80% of the carbon in the biochar remains permanently in the soil. Agronomic practices that demonstrate consistent benefits have not yet been developed, tested and extended to the agricultural community. Diverting the source material from landfills would likely add to the net GHG benefit by avoiding landfill methane emissions.

Both manufacturers indicate they will have agronomic products in quantities needed either for field trials or larger applications in 2018.

## Net Technical Capacity for Greenhouse Gas Reductions

### Carbon Farming in Boulder County, Colorado

We examined the net technical capacity for GHG reductions if mitigation practices were extended to all lands under fee-simple ownership or conservation easement by Boulder County or the City of Boulder. By "technical capacity", we refer to the expected total benefit if all practices were implemented on all lands under management by the county and the city. This assumes no restrictions in compost supply and uptake of the full suite of carbon farming practices. Figure 3 shows this technical capacity broken out for county lands, city lands, and other private lands. The technical capacity of all practices on all lands exceeds 170,000 metric tonnes (Mg) $CO_2e$ per year or 187,000 short tons $CO_2e$ per year.

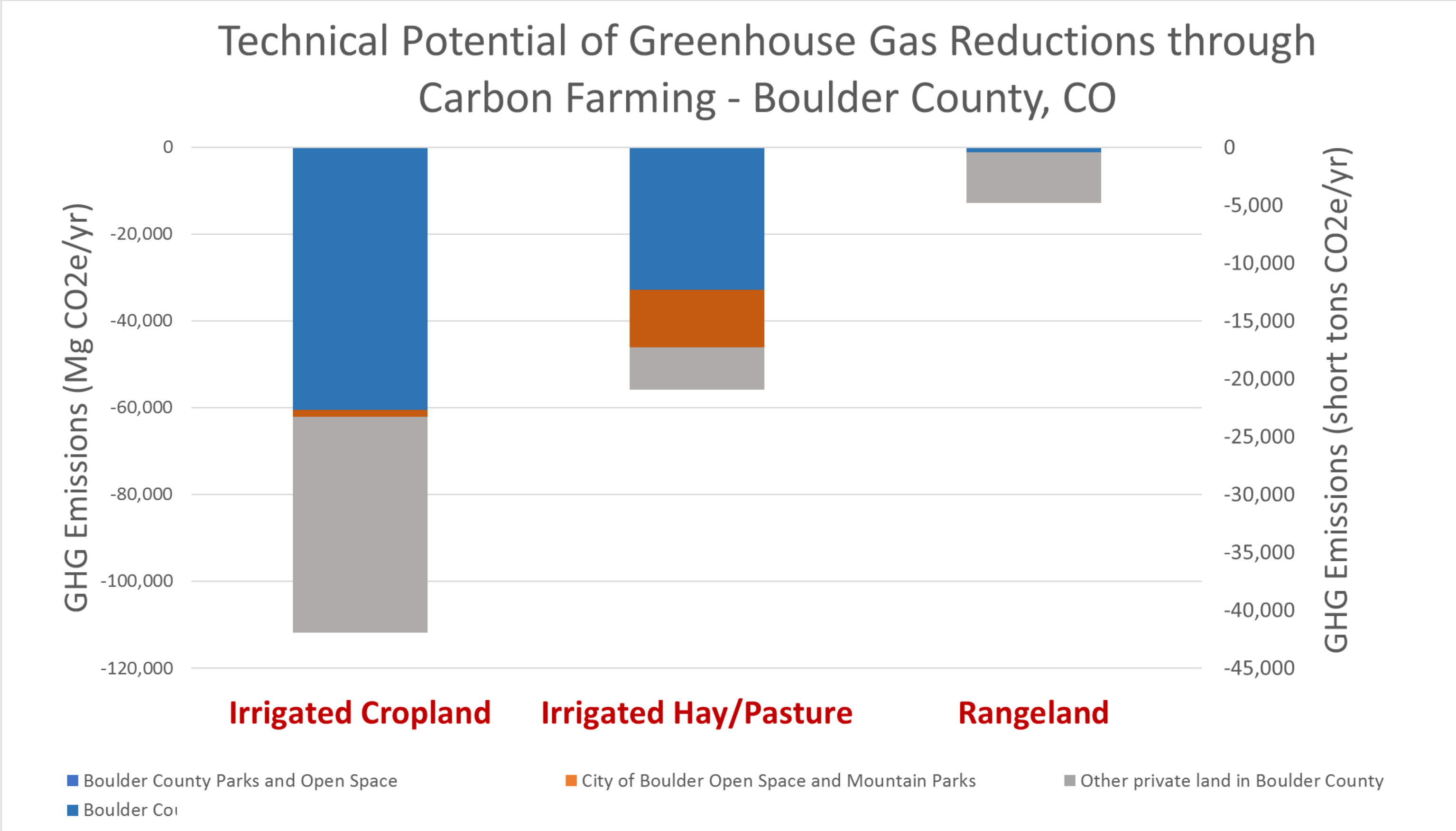


*Figure 3. Yearly technical potential of GHG mitigation practices for Boulder County Parks and Open Space, City of Boulder Open Space and Mountain Parks, and other agricultural lands in private ownership in Boulder County, CO. This assumes adoption of all five carbon farm practices, with approximately 50% of county-owned rangelands and none of city-owned native grasslands identified for potential compost amendments at this time.*

Figure 4 shows the technical potential on the basis of emissions reductions per unit land area for irrigated cropland. Adding windbreaks (11 metric tonnes (Mg) $CO_2$e/ha/yr or 4.9 short tons/acre/yr) provides the greatest benefit on a per area basis, but under this scenario only one acre of cropland would be planted to windbreaks for every 40 acres of cropland, or 2.5% of total cropland. When considered as an overall system benefit, the net carbon sequestration contribution is 0.28 metric tonnes (Mg) $CO_2$e/ha/yr or 0.12 short tons/acre/yr) for each ~40 acre field. Increasing the proportion of windbreak area to cropland area will correspondingly increase the net carbon sequestration benefits. Applying compost (6.9 metric tonnes (Mg) $CO_2$e/ha/yr or 3.1 short tons/acre/yr) provides the next largest overall potential benefit on a per acre basis. Utilizing cover crops (0.6 metric tonnes (Mg) $CO_2$e/ha/yr or 0.27 short tons/acre/yr), tillage reduction (0.35 metric tonnes (Mg) $CO_2$e/ha/yr or 0.16 short tons/acre/yr), and slow-release fertilizers or nitrification inhibitors (0.14 metric tonnes (Mg) $CO_2$e/ha/yr or .06 short tons/acre/yr) follow in relative importance.

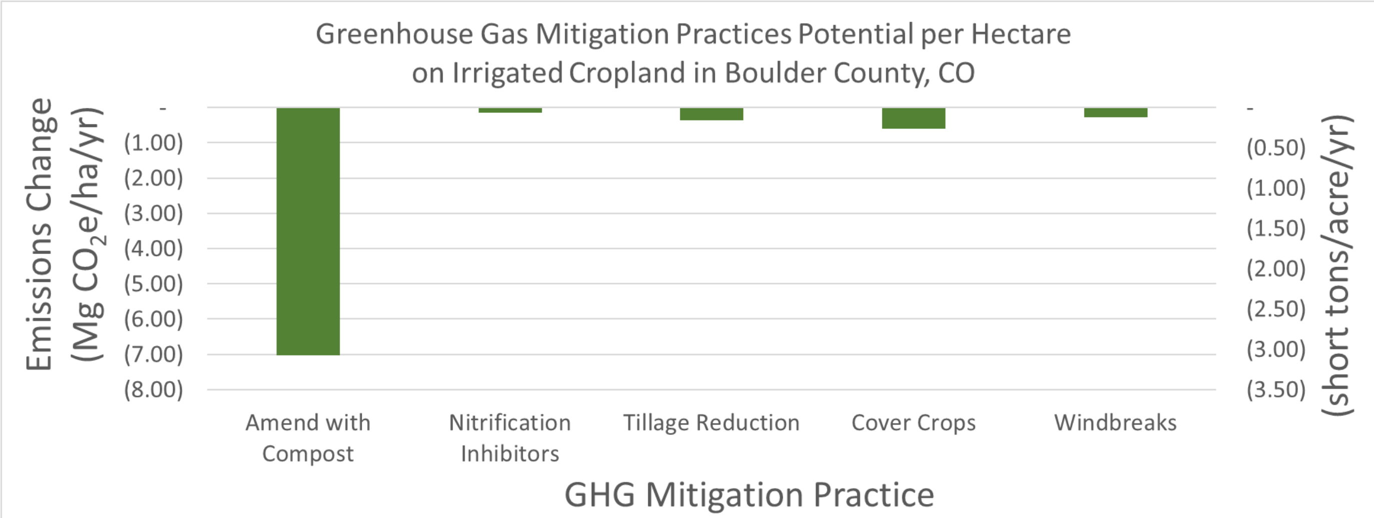


*Figure 4. Yearly technical potential of GHG mitigation practices on irrigated croplands for Boulder County and City of Boulder lands, on the basis of emissions reduction per unit area of land. Please note that the windbreak technical potential is based on one acre of planted windbreak for every 40 acres of hay/pasture land. The technical potential is 11 Mg $CO_2$e/ha/yr (4.8 short tons CO2e/acre/yr) on every planted acre of windbreak.*

Figure 5 shows the yearly technical potential on a per area basis of the three most feasible management practices for irrigated grass hay/pasture lands in Boulder County. Applying compost (6.8 metric tonnes (Mg) $CO_2$e/yr or 3.0 short tons/acre/yr) provides the largest overall potential benefit. Adding windbreaks (11 metric tonnes (Mg) $CO_2$e/ha/yr or 4.9 short tons/acre/yr) provides the greatest benefit on a per area basis, but under this scenario only one acre of cropland would be planted to windbreaks for every 40 acres of cropland, or 2.5% of total cropland. When considered as an overall system benefit, the net carbon sequestration contribution is 0.28 metric tonnes (Mg) $CO_2$e/ha/yr or 0.12 short tons/acre/yr) for each 40 acre field. Increasing the proportion of windbreak acreage to cropland will have a corresponding increase in carbon sequestration benefits. Using nitrification inhibitors or slow-release fertilizers (0.09 metric tonnes (Mg) $CO_2$e/yr or 0.04 short tons/acre/yr) follow in relative importance.

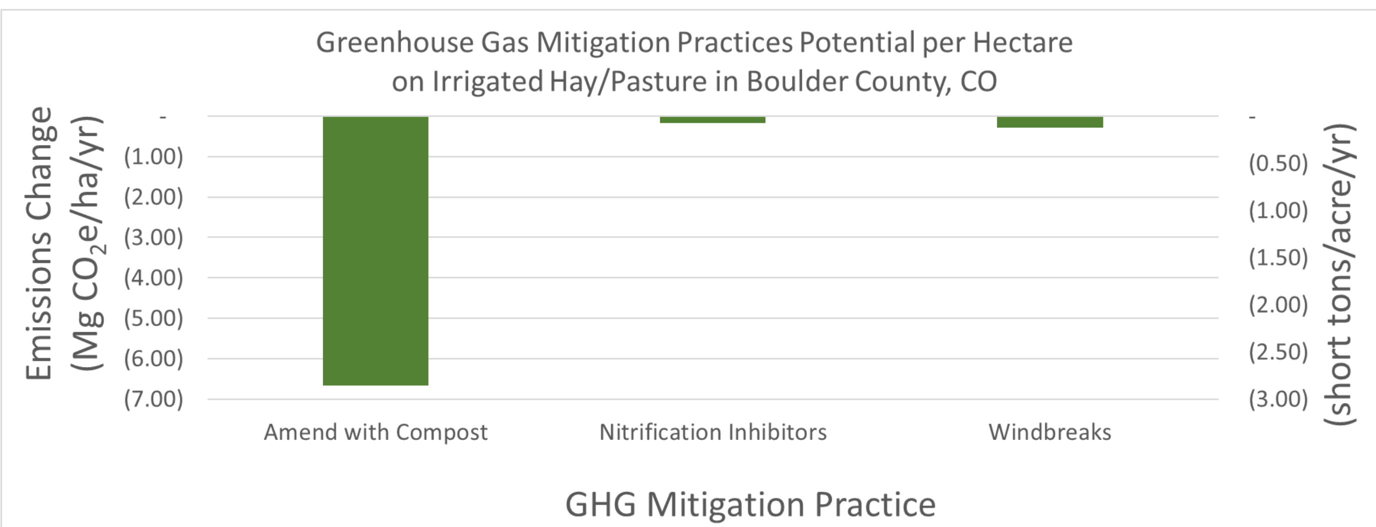


*Figure 5. Yearly technical potential of GHG mitigation practices on irrigated grass hay/pasture for Boulder County and City of Boulder lands, on the basis of emissions reduction per unit area of land. Please note that the windbreak technical potential is based on one acre of planted windbreak for every 40 acres of hay/pasture land. The technical potential is 11 Mg $CO_2$e/ha/yr (4.8 short tons CO2e/acre/yr) on every planted acre or windbreak.*

Figure 6 shows the technical capacity on the basis of emissions reductions per unit land area for degraded rangeland. Adding riparian buffers (5.5 metric tonnes (Mg) $CO_2$e/ha/yr or 2.5 short tons/acre/yr) provides the greatest benefit on a per area basis. For example, a 20 meter wide riparian buffer that is 500 meters long equals one hectare, or a 30 meter wide buffer 333 meters long also equals one hectare. Both would be expected to accumulate ~5.5 metric tonnes $CO_2$e/ha/yr (2.5 short tons/acre/yr) of carbon. This practice would apply to both perennial and ephemeral streams corridors on grazing lands that are currently degraded and do not have woody plant cover. Applying compost (0.64 metric tonnes (Mg) $CO_2e$/ha/yr or 0.29 short tons/acre/yr) provides the next largest overall potential benefit.

It is important to note that this estimate of carbon sequestration benefits from compost production on degraded rangeland could very well be conservative. Research by Ryals *et al.* (2013, 2015, 2016) studying compost amendments to degraded California rangelands found that soil ecosystem function changed significantly and net primary productivity increased beyond that expected from the net addition of plant-available nutrients in the compost. Amending degraded rangeland soil with compost appeared to induce a feedback loop that led to higher soil carbon stocks than were predicted from simply adding additional organic matter to soils. The mechanism for this process is yet to be fully understood at this point, and the soil carbon models used in the analysis in this report will be updated when those mechanisms are identified. It has not been confirmed that the same soil ecosystem processes would occur after compost amendment to degraded rangelands on the Colorado Front Range or other grasslands in the Intermountain West. This question is the focus of the research we propose later in this study.

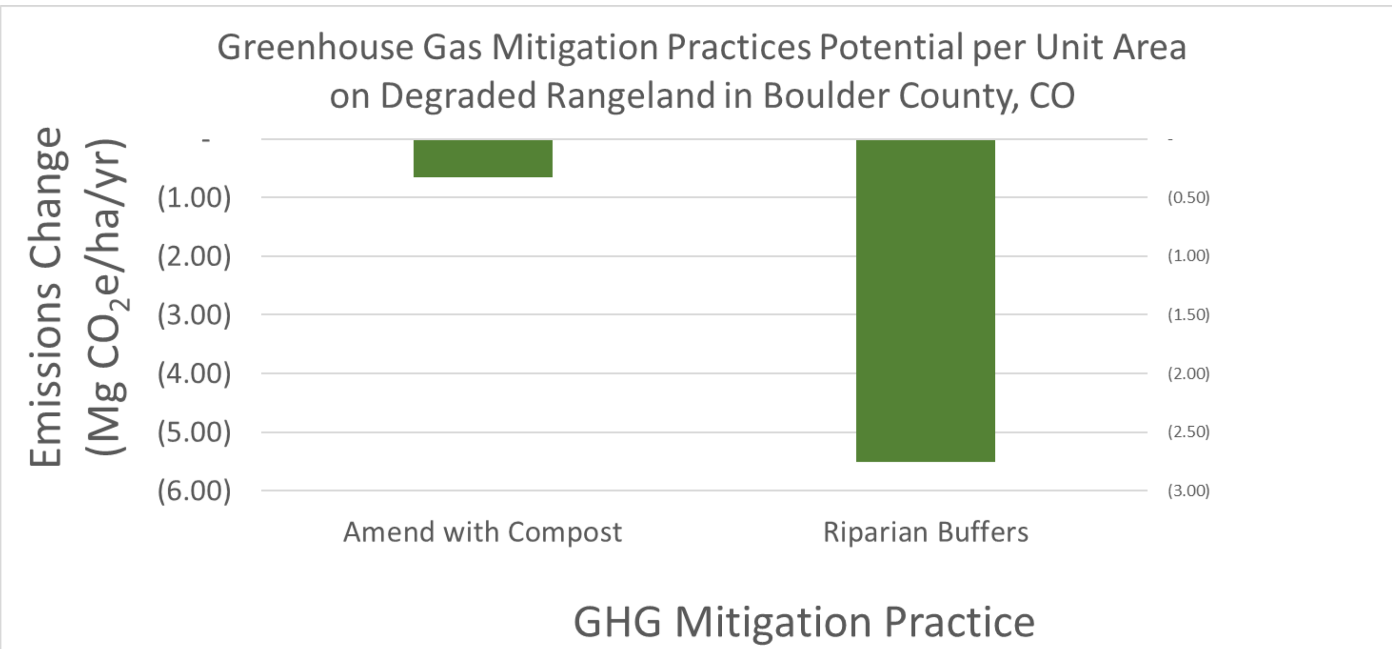


*Figure 6. Yearly technical potential of GHG mitigation practices on non-irrigated grazing land (rangeland) for Boulder County and City of Boulder lands, on the basis of emissions reductions per unit area of land. Note: The riparian buffer category does not assume a fixed ratio area of restored riparian buffers to area of degraded rangeland, it reflects a fixed potential benefit for every acre or hectare of degraded riparian buffer that is restored.*

## Economic Benefits and Costs of Potential Greenhouse Gas Management Practices

We analyzed the net change in the enterprise income associated with the most feasible GHG mitigation practices. This included the following potential factors:

- Additional income, such as through yield increases and forage increases.
- Cost of additional agricultural inputs, such as compost.
- Hauling and spreading costs.
- Reductions in cost for agricultural inputs, such as synthetic fertilizers.
- Avoided costs, such as reductions in fuel use through tillage reduction.
- Cost-sharing from the NRCS through EQIP.

All of the mitigation practices we recommend are eligible for NRCS EQIP cost-share funding except for compost application. When EQIP reimbursements are combined with other costs savings and yield improvements, all of practices except for compost additions can be accomplished at little to no cost, or in many cases, lead to higher net profit in the economic bottom line for the cropping systems.

The economic costs for compost application are more complicated. The short-term costs are significantly higher than the other practices, both on a per-acre basis and a cost-per-metric tonne of net benefit basis. These costs are likely to improve over time as soil carbon, nitrogen, phosphorus and other nutrient stocks increase and growers are able to further reduce synthetic fertilizer (and compost) additions over the long term. If costs for compost can be reduced to $20 per short ton delivered, the net per-acre cost drops to $56 per acre, and the net cost per metric tonne (Mg) of $CO_2e$ reduction is $19 ($17 per short ton). Economic cost savings that are currently external to compost production from landfill waste (diverting waste from landfills, avoided landfill tip fees, extending landfill life, and other costs) could contribute significantly to reducing the cost of producing compost if the price signal in those avoided costs was reflected in the final product price. Figure 7 through Figure 12 summarizes these costs per acre and the costs per metric tonne of greenhouse gas reductions for the different practices.

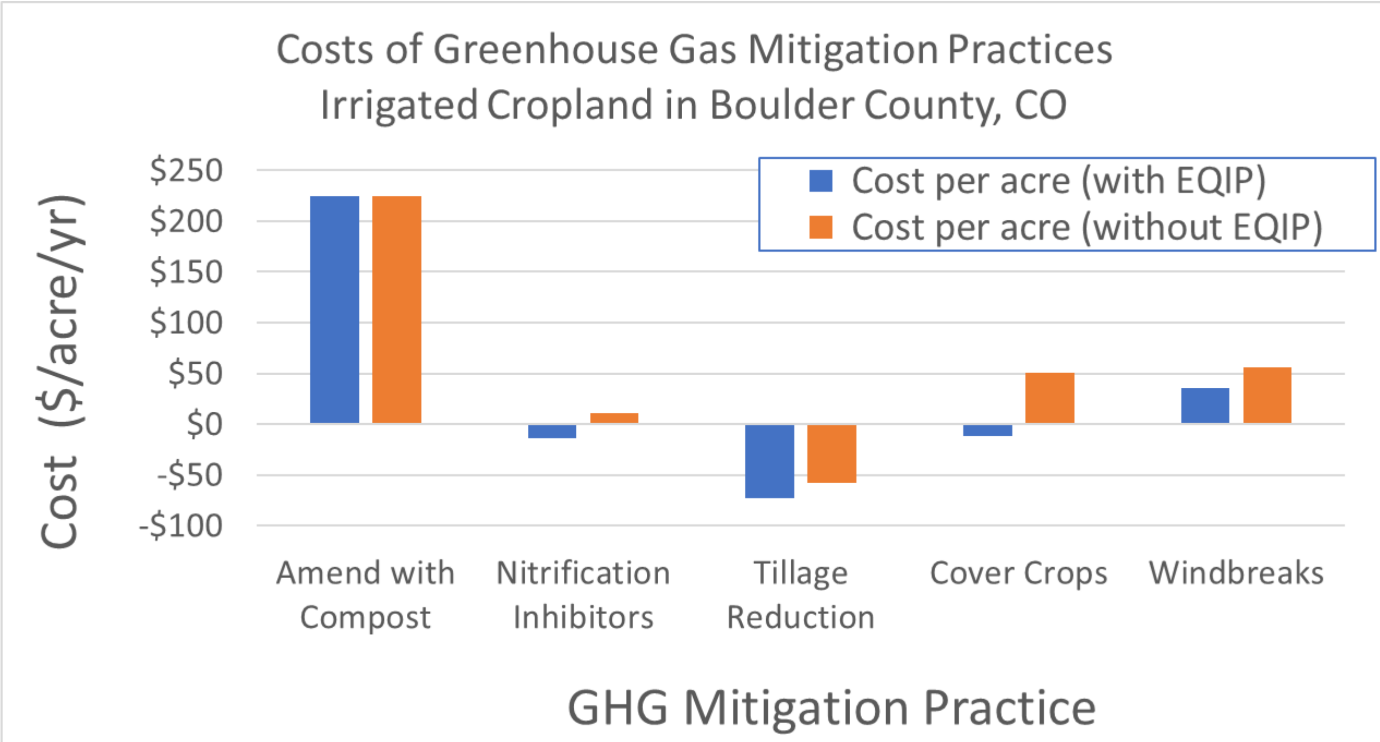


*Figure 7. Costs of GHG mitigation practices for irrigated cropland on Boulder County and City of Boulder Lands, on the basis of dollars per acre per year.*

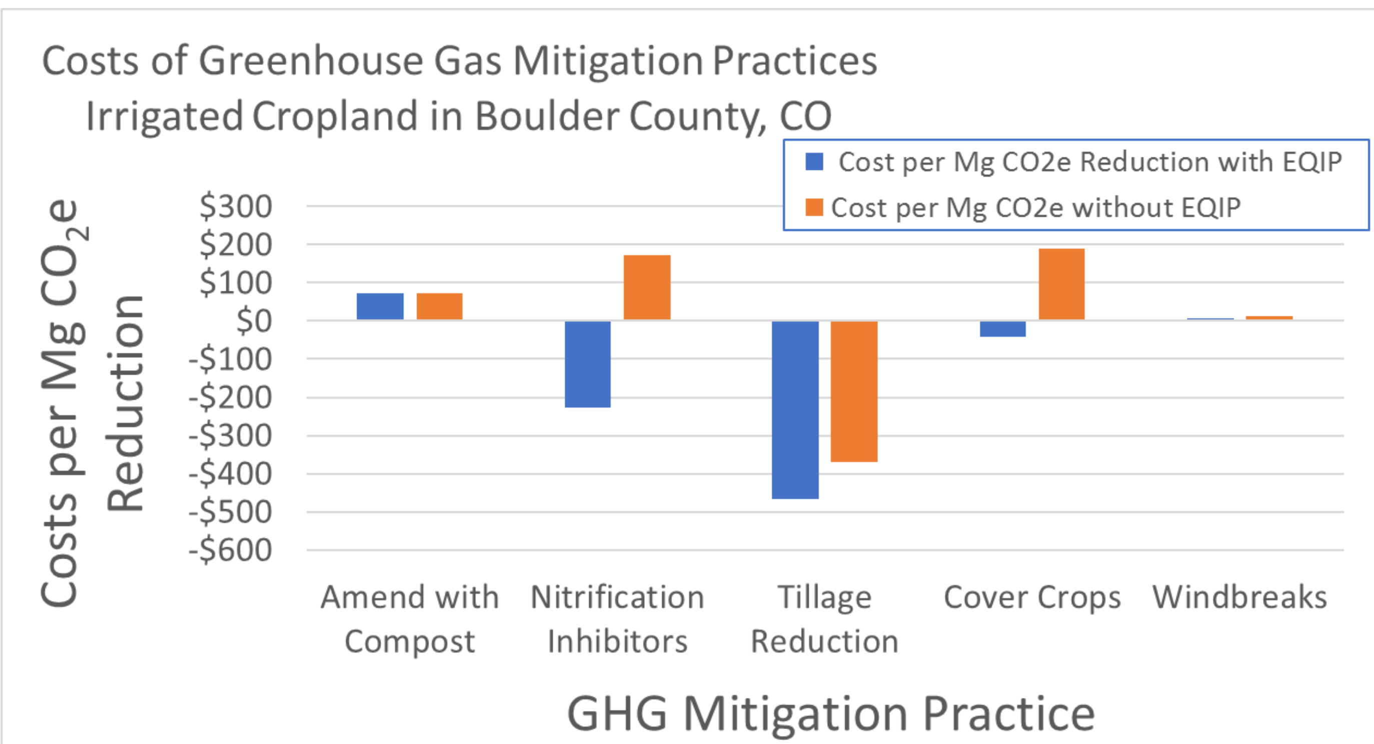


*Figure 8. Costs of GHG mitigation practices for irrigated cropland on Boulder County and City of Boulder Lands, on the basis of dollars per total net GHG reduction.*

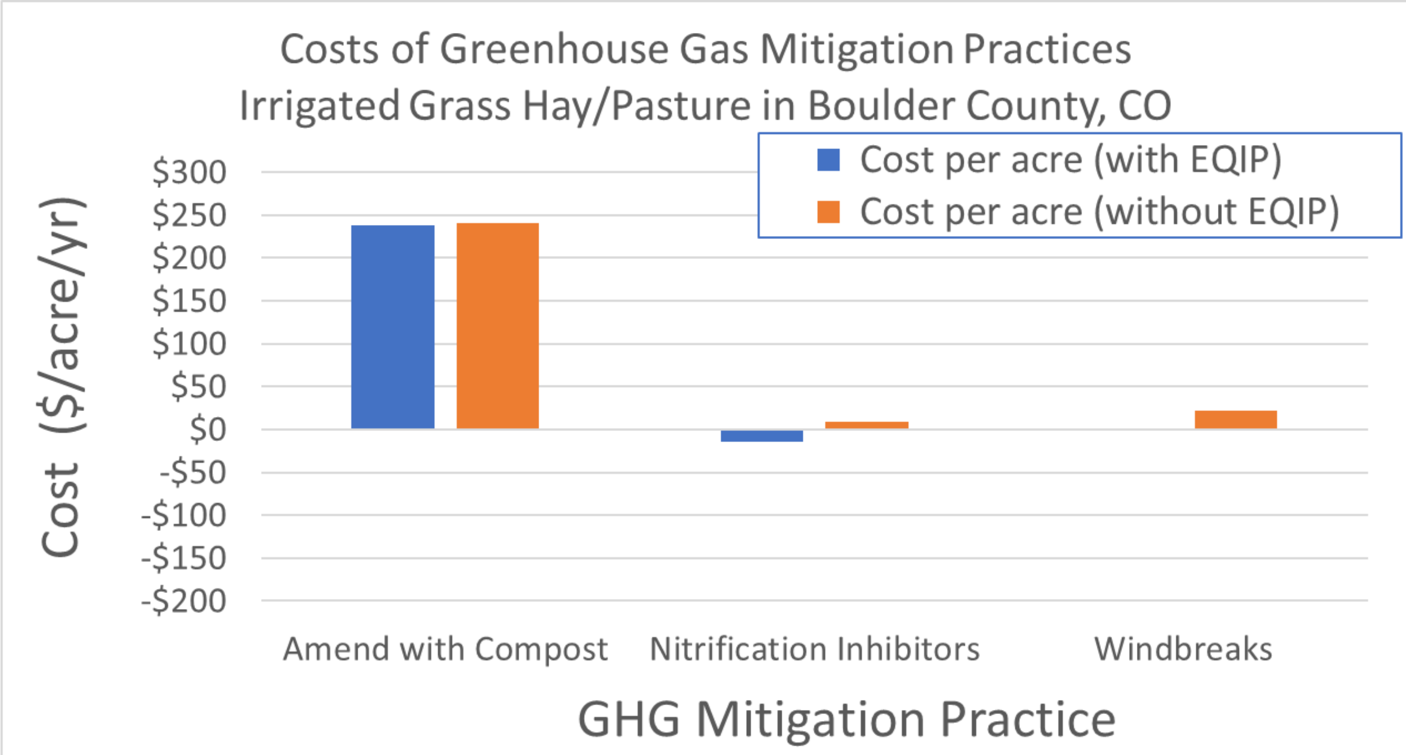


*Figure 9. Costs of GHG mitigation practices for irrigated grass hay/pasture on Boulder County and City of Boulder Lands, on the basis of dollars per acre per year.*

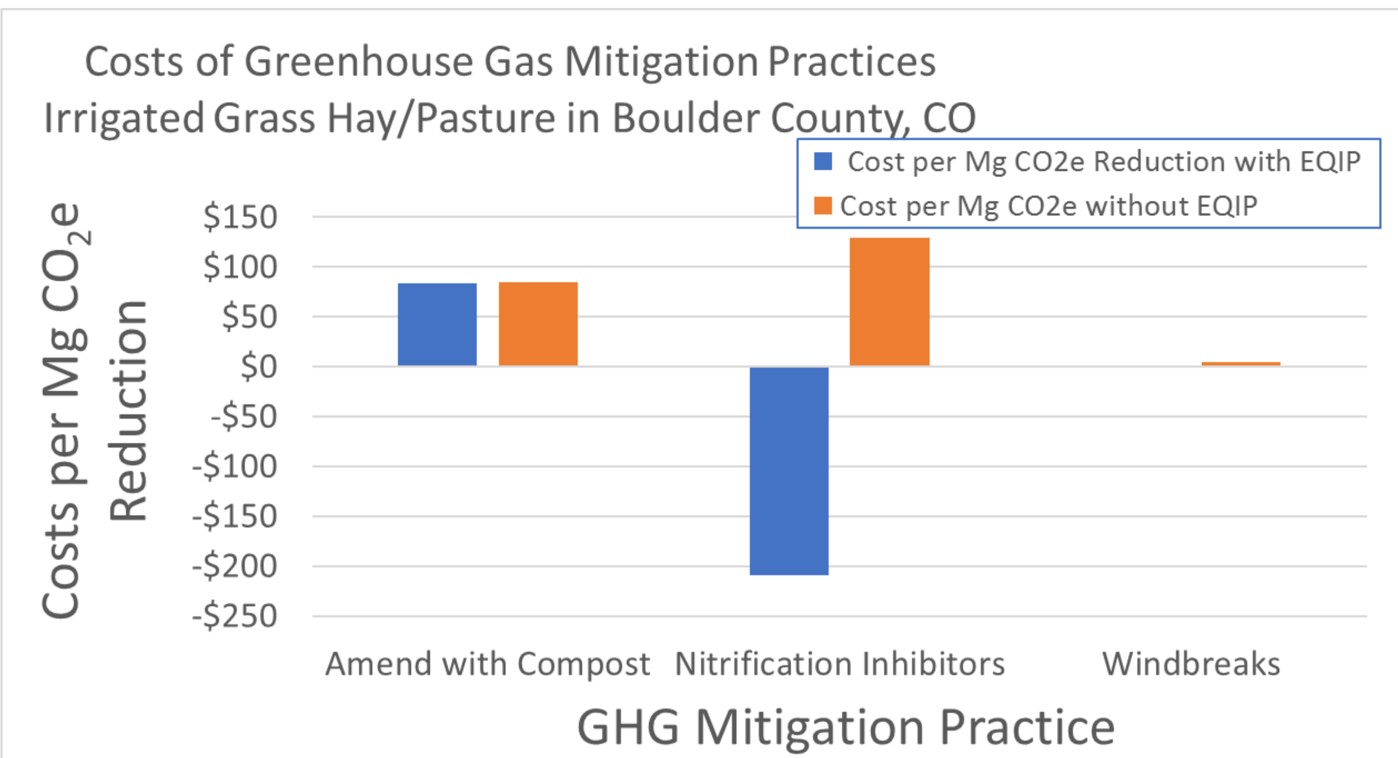


*Figure 10. Costs of GHG mitigation practices for irrigated grass hay/pasture on Boulder County and City of Boulder Lands, on the basis of dollars per total net GHG reduction.*

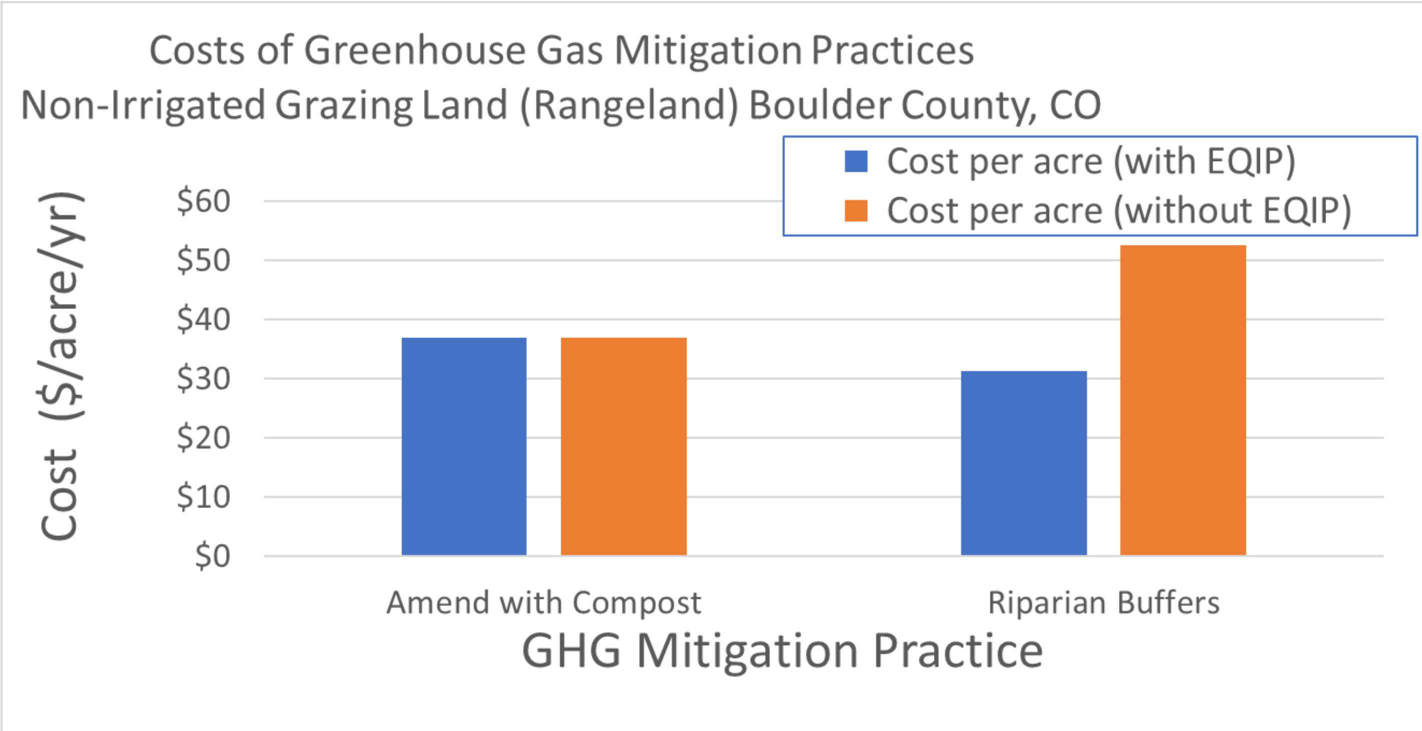


*Figure 11. Costs of GHG mitigation practices for non-irrigated grazing land (rangeland) on Boulder County and City of Boulder Lands, on the basis of dollars per acre per year.*

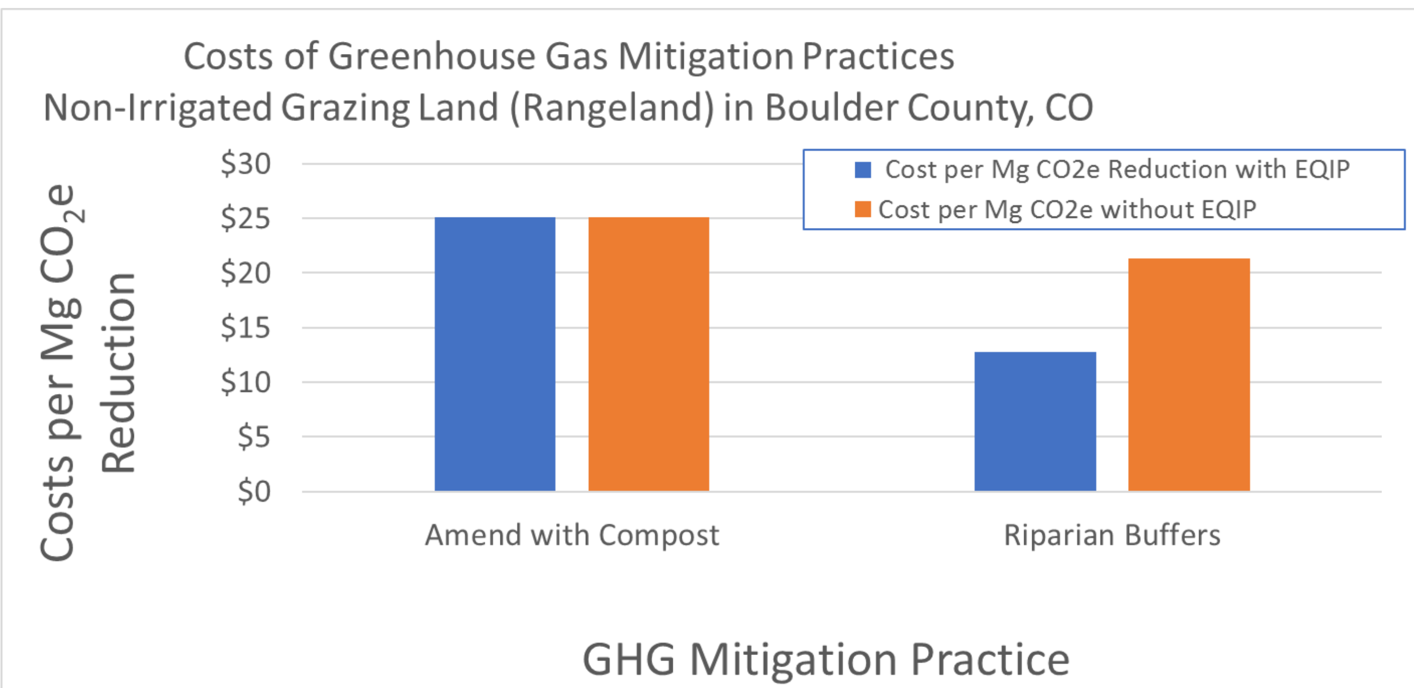


*Figure 12. Costs of GHG mitigation practices for non-irrigated grazing land (rangeland) on Boulder County and City of Boulder Lands, on the basis of dollars per total net GHG reduction.*

# Recommended Carbon Farming Practices

The practices described here ***apply equally to conventional and organic growers***, with the exception of slow-release fertilizers or nitrification inhibitors as they are synthetic fertilizer products. Differences in conventional and organic production techniques will likely drive the relative applicability of the other practices. Compost and/or manure use and cover crops are widespread in organic systems, whereas tillage reduction is not. Boulder County reported that approximately 15% of producers on Boulder County lands were either in or were transitioning to organic systems by 2016 (Boulder County 2016).

These practices also apply ***equally to homeowners and landscapers***. Substituting compost for synthetic fertilizers on lawns will lead to carbon sequestration benefits. Replacing synthetic fertilizers with slow-release fertilizers or utilizing nitrification inhibitors will reduce nitrous oxide emissions. Reducing and/or eliminating tillage and integrating cover crops into home gardens will lead to higher soil carbon sequestration. Planting trees in homes and municipal and industrial campuses will lead to net carbon sequestration in woody biomass where they meet landscaping needs and do not shade rooftop solar or solar gardens.

## Compost Production

Capture and diversion of organic materials from landfills and dairy manure lagoons has a large emissions benefit. The carbon sequestration and enhanced water holding capacity of the soils resulting from compost application also offers clear climate mitigation and resilience solutions. There do not appear to be any dairies operating manure lagoons in Boulder County, however several dozen are operated nearby in Weld and Larimer counties. At least eight dairies in Weld County, milking 750 cows or more, are operating within 20 miles of Longmont.

Hauling and spreading costs are high for compost. Siting production facilities within or near Boulder County has the potential to reduce production costs by approximately $28 per ton[2] for compost sourced completely from Boulder County materials, but produced in Weld County, by reducing the financial costs for hauling raw materials to composting sites and hauling finished compost to agricultural soils.

Policy and regulatory barriers should be further explored in order for the City and County to determine the most economically and technically viable options for compost production/procurement.

**Recommendation:** Much of the analysis and discussion on how to reduce the price of compost has focused previously on facility siting issues. We recommend shifting the focus from where to site a composting facility to how to reduce the overall cost of producing compost for agricultural purposes. This places needed emphasis on benefits from diverting the waste stream out of landfills and potentially leverages locally-produced manure and biosolids from within Boulder County.

There have been significant changes to area composting capacity since Matt Cotton's report was completed. Western Disposal's compost facility is closed. The Heartland biogas facility is currently closed, though the current owners are seeking a buyer whom they hope will re-open the facility. The only large-scale facility that is composting diverted landfill waste is A-1 Organics. The City of Boulder has implemented a Universal Zero Waste ordinance mandating compost collections for all sectors, which was discussed by the Cotton report but had not been implemented at the time it was

[2] Compost producers quoted a cost of $12.60 per ton to haul twenty-ton loads of compostable raw materials to compost production sites in Weld County, and an equivalent amount to haul the finished compost back to Boulder County. This represents about $38 in hauling costs alone to haul raw compostables from Boulder County to composting sites in Weld County and haul the finished compost back to Boulder County. Siting a production facility in Boulder County near raw materials and agricultural land would reduce hauling costs by at least 75% ($28),
assuming 2 tons of raw materials are shipped to the compost production site to produce 1 ton of finished compost hauled back.

written. Western Disposal is operating a waste transfer station, Stapleton's transfer facility in Denver has closed, and a new waste transfer station in Frederick has opened.

We recommend an update to the compost capacity analysis provided by Matt Cotton in 2014, to also include the following:

- Analysis of potential methods to reduce the price of compost, including addressing policy barriers, management of the compostable materials stream, reducing shipping costs, addressing economic externalities, and other factors.
- Analysis of site location possibilities based on available organic material streams identified in this report.
- Review of the following:
    - The potential opportunity for multiple (e.g. 3-7) possible sites for mid-scale, distributed generation with key community partners (CU Boulder, the City of Boulder Waste Water Treatment plant, Eco-Cycle, County Parks and Open Space, community composters).
    - Assess existing market economics with regards to medium-scale distributed compost generation.
    - Diverting biosolids and available horse manure generated within Boulder County into the compost production process.
- On-Farm Compost Production: Potentially the most cost-effective option for compost destined for the agricultural sector is on-farm production. On-farm compost production, or regionally-specific compost production by a group of interested agricultural stakeholders, co-operatives, or Conservation Districts would require a review of regulations regarding on-farm composting, potential rules changes, and a concentrated educational effort to foster best management practices.
- Align Rules to Realign the Marketplace: To identify and streamline all current incentives and regulations which touch organics diversion, processing and production of compost we recommend a review of all county agency policies and purchasing agreements and state policy that govern or influence organic material management and agricultural compost production and use.

## Sources of Raw Material for Composting

### Diverted Landfill Waste

Organic materials diverted from landfills (food waste, yard waste, paper products) represent the largest single category of potential composting raw materials. Cotton (2014) calculated that approximately 92,000 short tons per year of organic waste is generated within the county, which when deposited in landfills would produce 30,000 to 51,000 short tons of $CO_2e$ per year (27,200 to 46,300 metric tonnes $CO_2e$ per year), depending on the method used to calculate landfill emissions (CARB 2017). Cotton predicted that about 26,000 short tons of material might realistically be diverted from landfills for compost production. Approximately 13,000 short tons of organic waste is currently collected and composted (Ecocycle, personal communication).  If all 26,000 short tons of material were diverted, GHG emissions would be reduced by approximately 8,700 to 14,700 short tons of $CO_2e$ per year (7,900 to 13,400 metric tonnes $CO_2e$ per year). The greatest GHG reductions in the compost system life cycle in Boulder County appears likely to result from concerted efforts to divert all reasonably-recoverable organic materials from landfills into the composting stream.

**Recommendation:** Extend existing organic waste diversion efforts to the full extent practical and utilize that waste in the compost production stream.

### Wood

Using conventional methods to collect, shred, and haul harvested trees, approximately 44,000 short tons of compostable woody material could possibly be recoverable annually from fire mitigation efforts in and near Boulder County. The majority of this material (about 40,000 short tons) would come from fire mitigation activities on U.S. National Forest (USFS) lands, where trees removed in these activities are currently piled and burned. The remainder is currently processed and hauled from BCPOS and City of Boulder Open Space and Mountain Parks (OSMP) lands or from processing urban, suburban, and rural trees outside of forests. Assuming the costs to grind and haul the material from USFS lands is approximately the same as that for grinding and hauling from Boulder County lands, the material on USFS lands might become available for composting at a cost of about $44.50 per short ton in grinding and shipping costs, not including tipping fees. (T. Glowacki, personal communication). High costs could challenge the economic feasibility of recovering wood harvested from fire mitigation work on state and federal lands and diverting it into the composting stream.

There is significant interest in quantifying the potential regional biomass of green ash and white ash trees that may succumb to the emerald ash borer. No robust estimates of the biomass in green ash and white ash trees were available at the time of this study. Therefore we estimated the amount of wet wood biomass in green ash and white ash trees standing in Boulder County using the method described below. The method uses the best available information from city and county sources. The total biomass is estimated to be 198,000 short tons of wet wood biomass in green and white ash trees currently standing in Boulder County, derived as follows:

- We calculated the average tree wet biomass of green and white ash trees on the City of Boulder property based on their tree census (John Marlin, City of Boulder, Personal Communication) (1.2 short tons of biomass per tree). This was based on biomass regressions calculated by Truslove and McHale (unpublished data) from data gathered on ash trees in the Front Range, applied to the city of Boulder database of ash trees on city property. This database contained a sample of 5,490 trees, which is 7% of the green ash trees estimated in the city of Boulder (City of Boulder 2017). City staff cautioned that this dataset may under-sample smaller trees in riparian areas within the city, and so the mean per-tree value calculated may overestimate the per-tree biomass, though the size of that potential error term is unknown

- We estimated the total number of ash trees in Boulder County (167,000) by calculating a population-weighted sample of green ash trees based on the census from the city of Boulder (70,000 trees) and the city of Longmont (43,000 trees) and extending that per-capita sample to populated areas of the Boulder County Front Range, since green and white ash are popular landscaping trees. This estimate likely under-samples the trees found in riparian areas within the lower elevations of the County.

- If we assume a +\-50% confidence interval in this estimate, and also assume 10% of the trees in the county will be treated with pesticides to keep them alive and 90% of the trees will die from emerald ash borer over the next 5-10 years (City of Boulder, Boulder County, personal communication) then Boulder County might expect a biomass stream of 18,000 to 36,000 short tons of biomass per year available for composting or other uses in the next 5-10 years.

If this tree biomass were to be landfilled, the likely total methane emissions to the atmosphere are likely to be approximately 34,000 to 58,000 metric tonnes $CO_2$e (CARB 2017). If it were burned for fuel or other uses, the net trace gas emissions (methane, nitrous oxide, carbon monoxide) would average 6,000-11,900 metric tonnes $CO_2$e per year, with some fossil fuel emission offset likely though the amount would depend upon the use. If it can be composted and applied to agricultural soils, the overall net GHG reduction benefit averages 65,000 – 81,000 metric tonnes $CO_2$e, depending on the composting scenario. If it is used to produce biochar, the net GHG benefit is likely positive but is likely less than that of compost, and cannot currently be fully estimated.

**Recommendation:** Hauling costs from fire mitigation sites in the forests of the Front Range foothills and mountains are significant barriers to economic utilization of woody material. Utilizing wood from dying ash trees and other urban and suburban wood sources in the composting stream as it becomes available appears to be a more economically viable option for satisfying the need for bulking material in the composting process. Should a composting site or sites become available within or near Boulder County, we recommend diverting as much woody material as is practical into the composting stream and taking every practical step to avoid landfilling those materials. Material that is not practical to compost might be provided to biochar manufacturers where it is economically feasible and does not violate ash tree transportation restrictions.

### Biosolids

Like with other raw materials involved in the composting process, the main GHG reduction benefit involving biosolids in Boulder County would be to divert into the composting stream any class A biosolids currently being placed in landfills, and reduce the distance biosolids are hauled before they are land-applied.

**Recommendation:** Investigate this issue further to identify the following:

- Potential sources of biosolids within Boulder County that are landfilled but which would be suitable for composting.
- Potential sources of biosolids produced in Boulder County but which are land-applied outside of Boulder County, where the material may be safely applied on agricultural soils within the county.
- Potential sources of biosolids hauled outside of Boulder County for treatment, but which may be processed within the county and safely applied on agricultural soils within the county.
- Potential to increase compost production on Waste Water Treatment property

### Livestock Manure

Besides the horse manure and stall waste described above, there is a significant amount of cattle manure generated near Boulder County. The National Agricultural Statistics Service reports there are 96,600 dairy cattle in Larimer and Weld County. Manure at dairies in the region is typically stored in lagoons, from which it is pumped and scraped on an annual and semi-annual basis and spread on cropland and grazing land. Methane emissions from these lagoons is a significant source of greenhouse gases (IPCC 2007). Utilizing IPCC tier 1 methods (Eggleston *et al.* 2007) we can predict emissions to be 1.8 Mg $CO_2$e/head/year (2.0 short tons $CO_2$e/head/yr) from lagoon emissions on Larimer and Weld County if no manure separators are used to divert manure solids from lagoons. Dairies utilizing conventional manure separator technology (e.g. weeping walls, screw presses) can divert 40-50% of the manure solids from entering lagoons, reducing methane emissions by a corresponding amount. High-efficiency systems (conventional separator + centrifuge, or conversion to alternative collection methods such as “dry scrape” collection) can divert 80% or more of solids from lagoons.

Dairy manure is a high-value raw material for composting, and a large supply is available in the region relatively near Boulder County. Diverting manure solids from the waste stream in this region before it enters lagoons reduces GHG emissions by 0.29 metric tonnes $CO_2$e per metric tonne of diverted manure (IPCC 2007). The net GHG benefit of diverting manure from lagoons into the compostable materials stream and applying it to agricultural soils is approximately 0.55-0.61 metric tonnes $CO_2$e per metric tonne of manure in Boulder County, including avoided landfill emissions, avoided fertilizer manufacturing emissions, and carbon sequestration. The values are the same when expressed on the basis of short tons per year.

**Recommendation:** Investigate the cost-effectiveness and potential GHG reductions associated with cost-share investments in state-of-the-art manure separation technology in regional dairies in exchange for use of the manure solids in the compost stream for finished compost to be utilized on Boulder County agricultural lands. Investigate the economic and technical feasibility of purchasing manure based compost for a one time application to rangelands identified as appropriate for amendment application.

## Agricultural GHG mitigation practices

### Agricultural Greenhouse Gas Mitigation Systems

Research has shown that a systems approach achieves synergistic benefits for GHG mitigation compared with net benefits of individual practices (Eve et al. 2014). We recommend working with growers to combine practices in whole farm carbon planning and management to the maximum extent practical. Where combining practices is not practical, we recommend implementing individual carbon farming practices or combinations of practices.

In conversations with farmers, ranchers, and the staff within the Boulder city/county, we learned that the practicality of several GHG mitigation practices depends on the irrigation system on the cropland and pastureland involved. Reducing tillage and establishing cover crops are not always practical on flood-irrigated systems, but can be practical on sprinkler-irrigated systems where growers have late-season irrigation water available to them.

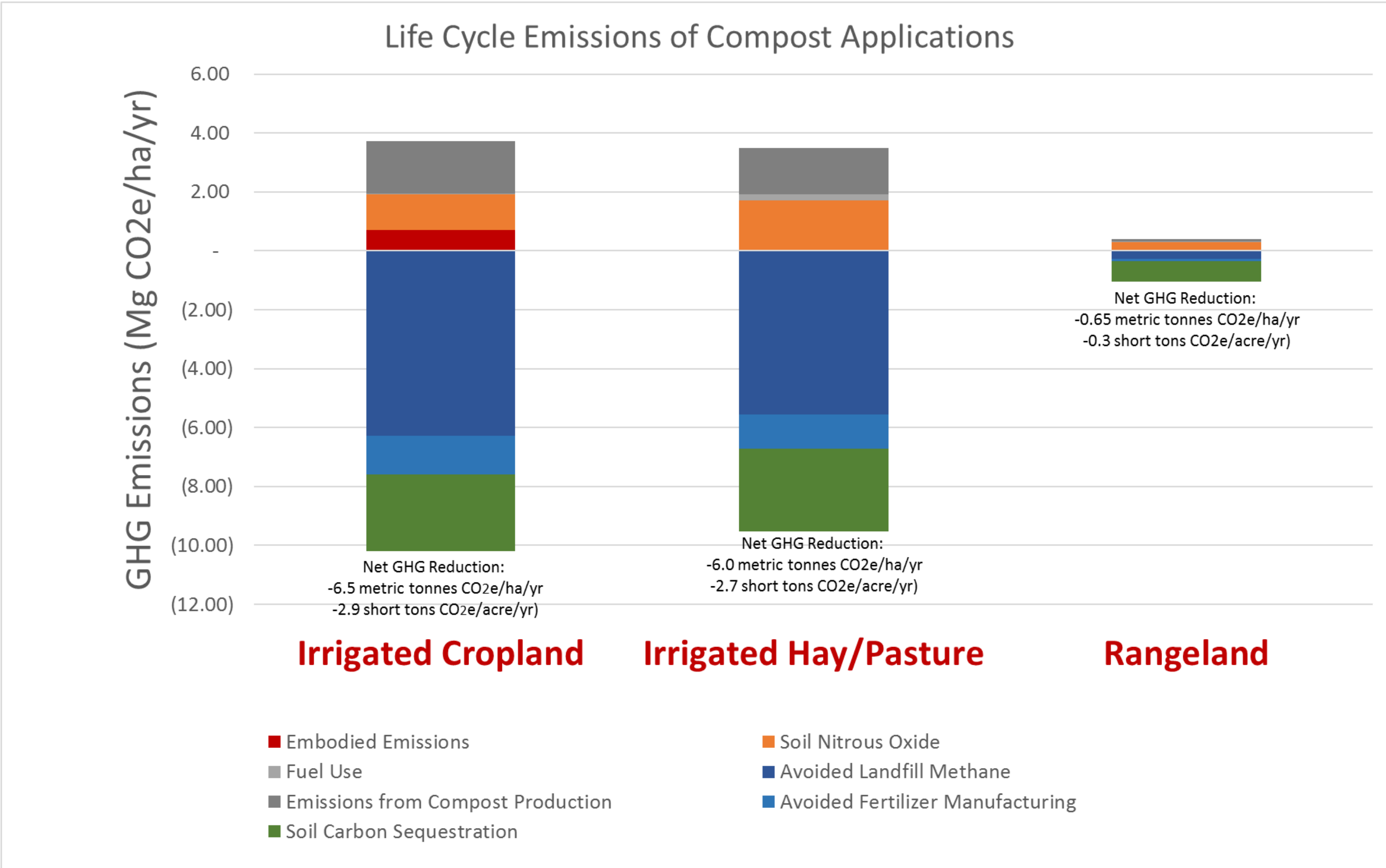


*Figure 13. Net GHG benefit of mitigation system on irrigated cropland, irrigated grass hay/pasture, and rangelands. Positive values indicate emissions to the atmosphere, and negative values represents net reductions in greenhouse gases to the atmosphere, including both reductions in trace gas emissions and net carbon sequestration.*

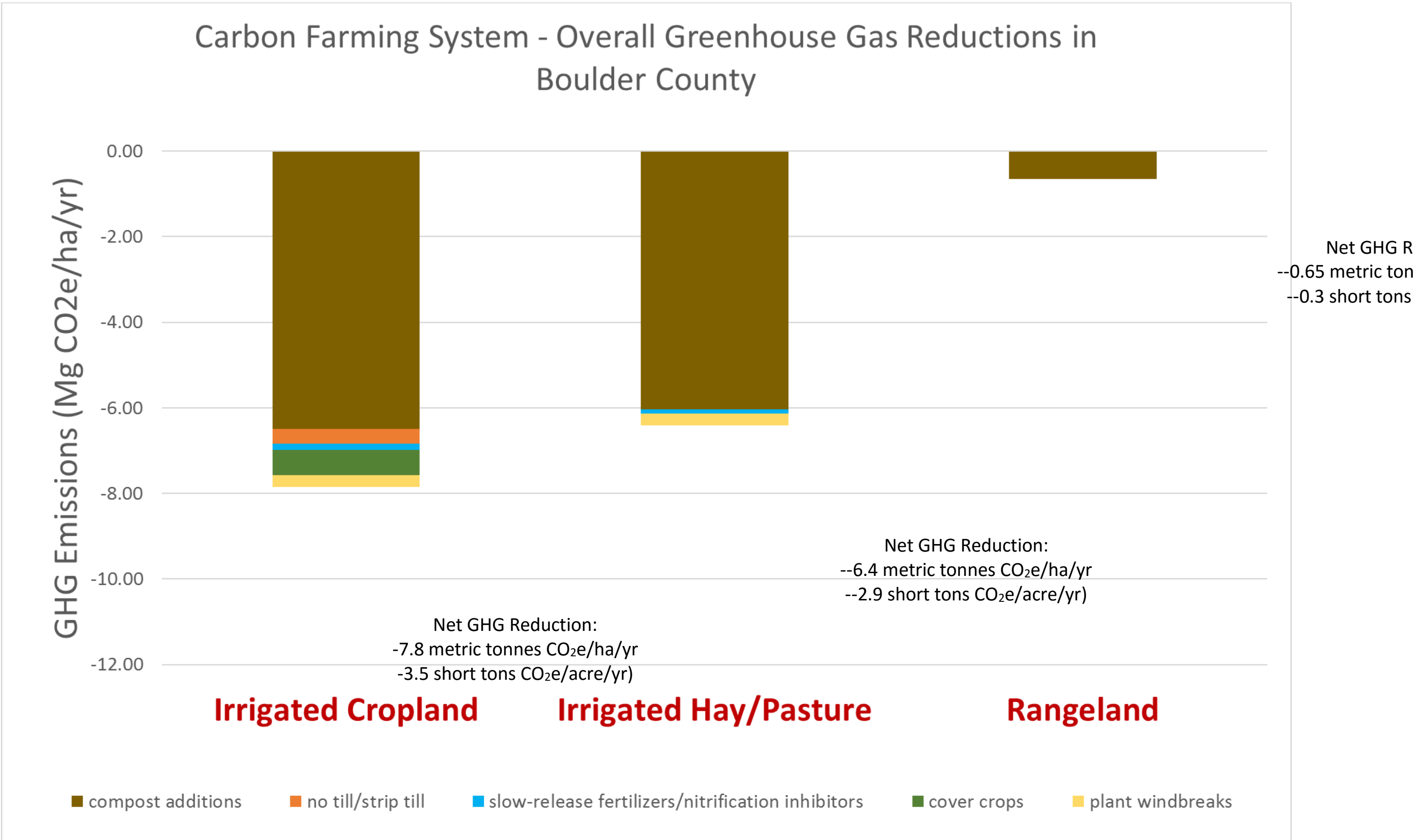


*Figure 14. Overall greenhouse gas reductions for carbon farming practices in Boulder County, CO, by land use and management category. A negative value represents a net reduction in greenhouse gases to the atmosphere, including both reductions in trace gas emissions and net carbon sequestration.*

**Cropland Recommendation:** On fields where late-season irrigation water is available through a sprinkler-irrigated system, work with producers to utilize the following GHG mitigation system:

- ***Apply compost derived from diverted organic landfill waste, livestock manure and wood to soils in agronomically-appropriate amounts, timing, and intervals.*** When utilizing compost sourced from landfill- and lagoon-diverted raw materials, the net GHG reduction factor is expected to be approximately 0.53-0.61 metric tonnes $CO_2$e per metric tonne of compost applied, within agronomically-recommended ranges (Easter *et al.* 2014). The values are the same when expressed on the basis of short tons.
    - Co-benefits:
        - Reduce long-term fertilizer requirements by 10% or more
        - Reduce irrigation water needs, extend water availability, increase drought resiliency as soil organic matter and soil water holding capacity increases.
    - Financial Benefits/Costs:
        - Financial benefits include reduced fertilizer requirements and increased crop yield. Studies typically show a 10-20% increase in commodity crop yields when compost is integrated into a cropping system (Lersch *et al.* 2014, Drury *et al.*2014). As a hypothetical example, a 10-15% increase in corn grain yield on a field yielding 150 bushels per acre at $4.50/bushel would increase gross income by $68-101/acre.
        - Long-term compost additions increase organic matter in soils, allowing producers to reduce fertilizer additions (synthetic or organic) over time. This can lead to significant cost reductions. We did not find peer-reviewed fertilizer reduction estimates from long-term economic studies of compost, however anecdotal evidence from other practices leading to increasing organic

matter indicates that fertilizer reductions of 30% or more in commodity crop systems are practical after a decade or more. As an example, assuming total fertilizer costs of $65-$85/acre per year for corn, long-term savings of $29-$40/acre/year may be possible. Higher reductions have been reported (Creque, personal communication).

        - Current material and shipping cost of compost from A-1 organics is $33-45/short ton for compost + delivery (depending on the product), trucked to zip code 80504 (near Longmont). No available contractors were found who could quote costs to spread compost on soil, however spreading costs of $2.50 to $7.00 per acre were described by crop consultants we interviewed. For an irrigated crop rotation in Boulder County involving 2 years of corn receiving 15 short tons/acre, 1 year of small grains receiving 8 tons of compost per year, 1 year of sugar beets receiving 17 short tons of compost per year, and 3 years of alfalfa receiving no compost, the net cost per year for compost amendments would be $285-$351.
        - To address concerns raised by producers regarding compost quality, we recommend using 5/8" minus or finer screened, thermophically-digested compost with a carbon-to-nitrogen ratio (C:N) of ~15 for use on cropland and irrigated hay/pasture (J. Creque and C. Ostrander, personal communication). This will reduce the likelihood of plastic contaminants and provide plant-available nutrients, specifically nitrogen, in the ratios appropriate for commodity crop production.
        - For non-irrigated pasture (rangeland) applications, we recommend using ¾" minus or finer screened, thermophically-digested compost with a C:N ratio of 25 (J. Creque, C. Ostrander, and J. Ippolito personal communication). This type of product provides the benefits of additional organic matter to the soil, but is less likely to promote the growth of invasive plants than a product with a lower C:N ratio and therefor higher plant-available nutrients.

- ***Convert from conventional/intensive tillage to no-tillage or strip-tillage***, and permanently end use of moldboard plows or similar implements. Nitrous oxide emissions will increase for a short time initially by approximately 38% but are expected to decrease permanently by 33% after 8-10 years (Eve *et al.* 2014). Soil carbon stocks in fields under this practice in Boulder County are expected to increase by 0.35 metric tonnes $CO_2$e/year (0.39 short tons $CO_2$e/year) for the next 20-30 years (Easter *et al.* 2014). If conversion to no-tillage or strip-tillage is not possible for practical reasons, convert to reduced-tillage systems, which improve soil carbon sequestration relative to intensive tillage, but not to the extent as does no tillage or strip tillage (Eve *et al*. 2014).
    - Co-benefits:
        - Reduce long-term fertilizer requirements by 10% or more.
        - Reduce irrigation water needs, extend water availability, increase drought resiliency as soil organic matter and soil water holding capacity increases.
        - Reduce soil erosion.
    - Financial Benefits/Costs:
        - Ruffin (2012) calculated that converting to minimum tillage in a corn-barley-sugar beet system reduced tillage costs by $17.47, $20.75, and $30.41 (in 2017 dollars) per acre in the corn, barley, and sugar beet acres, respectively.
        - A University of Nebraska study (Cropwatch 2017) showed cost savings of $43.76 per acre when producers converted from conventionally-tilled corn to no-till/strip-till corn.
        - Investing in seeding equipment for no-till and/or reduced-till systems can be a cost barrier for some growers due to the high capital costs of some equipment.

- ***Plant an agronomically-appropriate cover crop*** following small grains, silage corn, or any other crop where enough time remains in the growing season to germinate and establish a cover crop. This has the potential to increase soil carbon stocks in ranges intermediate between compost additions and conversion to no-tillage systems.
    - Co-benefits:
        - Increase soil water infiltration during rainfall/snowmelt/irrigation events

        - Reduce long-term fertilizer requirements by 10% or more
        - Reduce irrigation water needs, extend water availability, increase drought resiliency as soil organic matter and soil water holding capacity increases.
        - Reduce soil nutrient runoff and leaching during the shoulder seasons and winter.
        - Reduce soil erosion.
    - Financial Benefits/Costs:
        - Introducing cover crops typically adds costs in the short term, however it does improve soil fertility and reduce fertilizer needs in the long term. The NRCS (2016) reports a $22 cost/acre savings in an irrigated corn-corn-wheat-soybean system.

- If not using slow-release fertilizers, ***utilize nitrification inhibitors*** at the time of fertilizer applications and adjust/reduce fertilizer amounts to account for the plant-available nutrients in the soil and the extended period of fertilizer nutrients available to the plants. The net benefit of this practice will be to reduce nitrous oxide emissions by 21-51% (mean reduction of 38%) (Eve *et al*. 2014).
    - Co-benefits:
        - Reduce long-term fertilizer requirements by 15% or more.
        - Reduce soil nutrient runoff and leaching.
        - Increased nitrogen use efficiency.
    - Financial Benefits/Costs
        - Ferguson *et al.* (2003) and others found significant net financial benefits on irrigated corn when using nitrification inhibitors. This mirrors findings in multiple other studies, particularly when fertilizer amounts are calculated to meet crop demand according to soil test.

- If not using nitrification inhibitors, ***use slow-release fertilizers***, and adjust/reduce fertilizer amounts to account for the plant-available nutrients in the soil and in the applied compost and the extended period of fertilizer nutrients available to the plants. The net benefit of this practice will be to reduce nitrous oxide emissions by 12-30% (mean reduction of 21%) (Eve *et al*. 2014).
    - Co-benefits:
        - Reduce long-term fertilizer requirements by 15% or more.
        - Reduce soil nutrient runoff and leaching.
    - Financial Benefits/Costs:
        - Utilizing polymer-coated urea compared with urea or urea-ammonium nitrate can improve profitability significantly (Gagnon *et al.*2011).

- ***Plant combined pollinator strips/windbreaks on windward sides of irrigated fields and adjacent to perennial/ephemeral streams with little or no vegetative cover*** where irrigation water is available to establish trees and shrubs. One hectare of irrigated land devoted to a windward-side windbreak or restored riparian buffer in Boulder County can accumulate 11 metric tons $CO_2$e/year (4.8 short tons/acre/yr) or more for at least 30 years (Paustian *et al.* 2017) and increase net crop production on the field by 10% or more (Brandle *et al.* 2004, Zhou *et al.* 2011). This is roughly equivalent to the net benefits of no-till conversion on a 40-acre field. Ames (1980) found that windbreaks and riparian buffers reduce feed costs for over-wintering livestock by reducing caloric demands due to the shelter trees provide from severe winter weather.
    - Co-benefits:
        - Increased crop yield due to reduced evapo-transpiration and reduced soil surface evaporation in Boulder County's dry, windy climate.
        - Windbreaks/pollinator strips act as filter strips, reducing fertilizer runoff.
        - Pollinator habitat can increase crop yields for certain crops.
        - Using native trees, shrubs, grasses and forbs improves wildlife habitat.
        - Shelter for overwintering livestock.
    - Financial Benefits/Costs:
        - Increased net crop production by 10% or more (Brandle *et al.* 2004, Zhou *et al.* 2011).

Where fields are irrigated with sprinklers but late-season irrigation water is not available, we recommend working with producers to implement the combined practices and assess the likelihood of cover crop establishment on a year-by-year basis.

Where possible and to the extent financially feasible, work with producers and the Natural Resource Conservation Service through its EQIP program to convert from flood irrigation to sprinkler irrigation systems to facilitate the above systems-based approach.

**Rangeland Recommendation:** On rangeland with managed grazing, work with producers to ***identify degraded sites appropriate for compost application and apply compost derived from diverted organic landfill waste, livestock manure and/or woody material to soils in agronomically-appropriate amounts, timing, and intervals**.* When utilizing compost sourced from landfill- and lagoon-diverted raw materials, the net GHG reduction factor is expected to be approximately 0.53-0.61 metric tonnes $CO_2e$ per metric tonne of compost applied (0.53-0.61 short tons $CO_2e$ per short ton of compost). Plant community changes have been shown to occur in controlled studies after additions of raw manure, biosolids, and composted manure to soil (Blumenthal *et al*. 2017, Ippolito *et al*. 2010, Ippolito *et al*. *2009*). Land managers would need to assess their management objectives to ensure compost addition is a good fit. Intact and relatively undisturbed native grasslands would likely not be good candidate sites to receive compost additions (City of Boulder and Boulder County Staff, personal communications). Degraded rangeland, where compost addition can aid in restoration efforts or achieving other management objectives, are likely to be better fits for compost additions. Livestock managers would likely need to pay closer attention to rangeland production and conditions and adjust grazing intensity and timing since compost applications are likely to stimulate plant growth on rangeland through added nutrients, increased nutrient cycling through the soil microbial community, and higher soil water holding capacity due to increased organic matter in the soil.

- Co-benefits:
    - Extend water availability, add plant-available nutrients, increase drought resiliency as soil organic matter and soil water holding capacity increases.
- Financial Benefits/Costs:
    - Financial benefits include increased water holding capacity and likely increases in forage yield. We found no published economic analyses of compost addition on semi-arid rangelands, although such work is underway in California. In California rangelands, forage production increased 41-76% (depending on the ecosystem) after a single 14 metric tonne per hectare (6.2 short tons/acre) application of compost.
    - Current material and shipping cost from A-1 organics is $33-45/short ton for compost and delivery, trucked to zip code 80504 (near Longmont). The cost for compost delivered (2017 dollars) to rangeland sites in Boulder County receiving 2 short tons/acre every 5 years would be $18-23/yr (not including compost spreading costs, which are unknown).

- ***Restore riparian vegetation to perennial/ephemeral streams with little or no vegetative cover***. One acre of non-irrigated land devoted to a restored riparian buffer in Boulder County can accumulate ~5.5 metric tons $CO_2e$/ha/year (2.4 short tons $CO_2e$/acre/yr) or more for at least 30 years (Paustian *et al.* 2017) and increase net forage production on the adjacent downwind field by 10% or more (Brandle *et al.* 2004, Zhou *et al.* 2011).
    - Co-benefits:
        - Increased forage yield due to reduced evapo-transpiration and reduced soil surface evaporation in our dry, windy climate.
        - Using native trees and shrubs improves wildlife habitat.
    - Financial Benefits/Costs:
        - Riparian cover can provide critical shelter to livestock during bad weather or hot and dry conditions, reducing winter feed requirements and increasing feed efficiency in summer weather. Livestock will need to be fenced out of riparian areas in order to re-establish them to woody cover. Allowing livestock to utilize shade or windbreaks for cover will require gates and/or selective access, which could increase costs and require additional management.

# Further Study

## Compost Applications on Degraded Rangelands

Adding nutrients to grazing land through compost additions, while increasing water holding capacity, are likely to increase plant production. Like with any management activity, this is likely to require monitoring to assess the effectiveness of the applications and require changes in the timing and extent of livestock grazing to ensure the desired species composition and plant cover are maintained or achived. Research indicates that organic matter additions on grazing land do affect plant communities in trials where no additional management activities were used. That is, where organic matter additions were made but there was no livestock grazing, herbicide treatment, or other activities, the plant community did show shifts in species composition. Some invasive species increased in abundance and/or biomass, but without any management activities targeted to reduce their presence in favor of native species (Ibid).

We recommend implementing a set of research trials in conjunction with the Colorado Natural Resources Conservation Service on rangeland where livestock grazing occurs, and where county and city staff recommend compost may be applied without conflicting with other desired ecosystem values.

## Compost Feedstock Supply and Cost Reductions

Farmers and Ranchers working on city and county property indicated that the price of compost delivered to agricultural lands is a significant barrier to cost-effective utilization of the resource. Current compost prices do not take into account economic externalities related to feedstock supplies and management, such as avoided landfill tipping fees, avoided costs associated with extending landfill lifetimes, potential avoided hauling costs, and greenhouse gas emissions from compostable material deposited into landfills. In addition to this, we were unable to compile a firm estimate of the amount of horse manure and biosolids generated within the county and which may be composted and used on agricultural lands. More work needs to be done in this area to develop a firm estimate of the amount of compost feedback is available from these sources.

In collaboration with contractors Calla Rose Ostrander and Dan Matsch, CSU proposes to follow up the Phase 1 effort with additional research into the following:

1. Potential policy state and local barriers to cost-efficient compost production and utilization.
2. Opportunities to address externalities affecting the cost of compost production and compost capacity.
3. Improve estimates of compostable biosolids and horse manure production within the county.

Completing this work will help guide Boulder County in setting short-term and long-term policies to improve the overall utilization and effectiveness of compost utilization, carbon farming, and greenhouse gas mitigation in the future. Deliverables will include a final report by the early summer of 2018 along with presentations to elected officials, county staff, advisory boards and stakeholders.

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