Claims that Livestock Grazing Enhances Soil Sequestration of Atmospheric Carbon are Outweighed by Methane Emissions from Enteric Fermentation: A Closer Look at Franzluebbers and Stuedemann (2009)

Mike Hudak
mikehudak@mikehudak.com
www.mikehudak.com | www.westernturfwars.com

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Prologue

I wrote this essay for two primary reasons. First, I wanted to demonstrate how a research project about mitigating global climate change, though presumably truthful in its methods and findings, could nevertheless be false (as regards the mitigation) within a broader environmental context. And second, I wanted to provide a tutorial, primarily for animal and environmental advocates, that shows essential factors to consider when evaluating any research that purports to demonstrate that cattle grazing can mitigate global climate change.

Franzluebbers and Stuedemann's Cattle-Based Atmospheric-Carbon-Reduction Protocol Ignores Enteric-Fermentation-Produced Methane

Agricultural publications proclaim the good news: "Cattle Pastures May Improve Soil Quality"[1] and "USDA Weighs In: Grazing Good for Soil & Environment."[2] Both headlines refer to the findings published in Franzluebbers and Stuedemann (2009)[3] (hearafter referred to as F&S)—research demonstrating that soil sequesters more atmospheric carbon (C) as pasture managed under "low grazing pressure" (LGP) than as "unharvested" pasture (UH) left ungrazed by cattle, or as pasture subjected to "high grazing pressure" (HGP).

While this result may be correct, the study neglects to account for the methane (CH_4) (a short-acting, but potent greenhouse gas) that is produced through enteric fermentation[4] and emitted by the study's cattle into the global climate system. Without such an accounting, it is impossible to conclude that any of F&S's grazing management prescriptions are superior to land management that excludes cattle (as regards reducing the greenhouse gas impacts of atmospheric C).

F&S Find LGP Management is Superior to UH

F&S arrived at their conclusion by evaluating the factorial combination of nutrient source and forage utilization on soil-profile distribution (0–150 cm) of soil organic carbon (SOC) during 12 years of management on Typic Kanhapludult (Acrisol) in Georgia, USA. In measuring the concentration of SOC (p. 31, Table 2) and change rate of SOC (p. 33, Table 4), the authors found that grazing's superiority (compared to ungrazed management) was greatest at soil depth 0–30 cm, with statistical significance decreasing as soil depth approached 150 cm.

Estimating the Mass of Enteric-Fermentation-Produced CH_4 that Results from F&S's LGP Protocol

Based on F&S's finding of lessening statistical significance below 30 cm, I will primarily focus on soil depth data in the range of 0–30 cm when comparing the change rate of SOC sequestration to CH_4 emitted by cattle grazing on LGP test plots.

With management averaged over three nutrient source treatments accessed to a soil depth of 30 cm, I compute from the data (p. 33, Table 4) a rate of change for SOC of 1.40 Mg ha^{-1} $year^{-1}$ for LGP management compared to only 0.797 Mg ha^{-1} $year^{-1}$ for UH management. At face value this result appears to support the conclusion that grazing is superior to non-grazing in mitigating global climate change, as the grazed pasture sequesters approximately 1.76 times as much C as the ungrazed one.

But as noted above, there's a significant omission in this analysis as regards CH_4, which in the short term has even greater potential than CO_2 to produce global warming. F&S address neither the mass of CH_4 produced by their cattle through enteric fermentation nor the mass of atmospheric CH_4 that is being absorbed by the soil upon which the cattle graze. Despite the absence of this information in their article, reasonable estimates can be made.

Let's first consider the mass of C emitted as CH_4 by the steers that grazed the pasture. The LGP trials consisted of 5.8 steers per hectare grazing for 140 days per year during the first 5 years of the study, and for approximately 310 days per year during the remaining 7 years. Although CH_4 emitted by a typical steer ranges from 60 to 71 kg per year,[5] as a concession to ranching advocates, I'll calculate CH_4 emissions based on the low end of the range (60 kg $year^{-1}$). And I'll attribute to the steers the CH_4 emitted only during the time they were present on the test plots during the 12 years of the study.

The mass of CH_4 emitted by the steers per hectare per year can be estimated by computing the weighted average of the annual CH_4 emissions per steer over the two periods of the 12-year study, and then multiplying by the number of steers per hectare. This yields 0.228 Mg CH_4 ha^{-1} $year^{-1}$, of which about 75% by mass is C (0.170 Mg C ha^{-1} $year^{-1}$). From the perspective of ranching advocates this still looks like a favorable result, as the mass of C sequestered by the soil (1.40 Mg C ha^{-1} $year^{-1}$) is more than 8.2 times the mass of C emitted by the steers. But this balance in favor of the soil sequestering atmospheric C may be less significant than it appears at first glance, as there are two essential factors about CH_4 yet to consider.

CH_4's Global Warming Potential

The relative ability of CH_4 compared to CO_2 to trap heat in the global climate system over a given time frame is expressed by CH_4's "global warming potential" (GWP).[6] Internationally accepted values for CH_4's GWP (with climate-carbon feedback) are "34" over a 100-year interval (GWP_{100}) and "86" over a 20-year interval (GWP_{20}).[7] Stated otherwise, over a 20-year interval, a given mass of CH_4 would have the same effect in the global climate system as a mass of CO_2 that is 86 times greater than that mass of CH_4.[8]

Authors of climate-related articles have usually considered CH_4's impact over a 100-year period. But in 2013, the IPCC noted that "there is no scientific argument for selecting 100 years compared with other choices."[9] Moreover, the IPCC found that at the 20-year timescale, total global emissions of CH_4 are equivalent to over 80% of global CO_2 emissions.[10] In that light, Howarth (2014) argued for focusing on the 20-year, rather than the 100-year, period based on "the urgent need to reduce methane emissions over the coming 15–35 years."[11]

Soil Sequestration of Atmospheric CH_4

The second CH_4-related factor to consider in regard to F&S's research is the amount of sequestered SOC that is derived from CH_4, rather than from CO_2. Although I know of no results reported from the same region as their research, studies conducted elsewhere provide a reasonable upper bound for the mass of this CH_4.

For example, Wang et al. (2015)[12] examined soil sequestration of CH_4 on land grazed by sheep at the Guyuan State Key Monitoring and Research Station of Grassland Ecosystem (China). Climate characteristics here differed significantly from those of the Georgia site studied by F&S. Whereas the latter site, at latitude 33° 22' N, has experienced long-term mean annual temperature of 16.5°C and rainfall of 1250 mm, the Wang et al. site at latitude 41° 44' N (more than 945 km farther north), has long-term mean annual temperature of 1.4°C and precipitation of 450 mm—hence much cooler, with shorter growing season and only one-third the precipitation of the F&S site.

Of the grassland management protocols that Wang et al. studied, "moderately grazed" was found to sequester the greatest mass of CH_4—an average daily uptake by soil of 0.02781 kg ha^{-1} day^{-1}. To yield the most favorable outcome for the ranching industry, I'll extrapolate this value to the duration of an entire year rather than to just the average of 239 days per year that the steers remained on the landscape over the 12 years of the F&S study. This yields a soil sequestration rate of 0.01015 Mg CH_4 ha^{-1} $year^{-1}$, approximately 4.4% of the average annual mass of CH_4 emitted by the F&S steers through enteric fermentation.

Another study[13] conducted in China examined CH_4 sequestration on three types of steppe: desert, typical, and meadow. As in the previously mentioned study by Wang et al., all locations studied are at high latitude (more than 940 km north of the F&S site), and hence have much lower annual temperatures than the F&S site—only slightly above the freezing point of water. Similarly, all these steppe locations are characterized by annual mean precipitation ranging from a third ("typical" and "meadow" sites) to less than a fourth ("desert" site) that of the F&S site. Consistent with Wang et al., "low grazing" (among the grazing protocols examined) yielded the highest rate of CH_4 sequestration. Extrapolating to a one-year duration the mean values thus obtained,[14] yield sequestration rates as follows: desert steppe: 0.0114 Mg ha^{-1} $year^{-1}$, typical steppe: 0.00860 Mg ha^{-1} $year^{-1}$, and meadow steppe: 0.00601 Mg ha^{-1} $year^{-1}$.

Allen et al. (2009)[15] examined soil sequestration of CH_4 in pasture and forest sites in three different climate regions (Temperate, Mediterranean, Subtropical) of Australia. Of the three regions, the Mediterranean climate region most closely approximates the F&S site in terms of mean annual temperature (15.7°C), but exhibits a much lower annual precipitation range (696–812 mm) and hence much lower mean annual precipitation. In each climate region Allen et al. examined three paired pasture-forest sites representing three key stages of forest stand development. For the purposes of my analysis of the F&S study, I need only consider the CH_4 sequestration in the pasture portion of each site. As reported in Table 4, p. 453 of Allen et al., the annual CH_4 flux (mg m^{-2} $year^{-1}$) for the Mediterranean climate region sites are -96, -52, and -47. (Note that Allen et al. never uses the word "sequestration" in regard to the transfer of a greenhouse gas between the atmosphere and soil. Instead the "flux" of a gas is stated as being either positive or negative, "negative" meaning that the gas is passing from the atmosphere into the soil. For my examination of results from Allen et al., I will retain their terminology.) The average of these values is -65 mg CH_4 m^{-2} $year^{-1}$ which can be equivalently written as -0.00065 Mg CH_4 ha^{-1} $year^{-1}$. This mass of CH_4 represents only about 0.285% of that which is annually emitted by the F&S steers.

Of the three climate regions studied, Allen et al. report (Table 4, p, 453) that the Temperate region pasture sites exhibited the highest rates of CH_4 sequestration by soil: -107, -187, and -119 (mg m^{-2} $year^{-1}$). Averaging to -137 mg CH_4 m^{-2} $year^{-1}$ (equivalently written: -0.001377 Mg CH_4 ha^{-1} $year^{-1}$), this mass represents approximately 0.6% of the CH_4 annually emitted by the F&S steers.

Due to greater similarly of climate, it is more likely that the soil sequestration rate of CH_4 at the F&S site in Georgia is closer to that of the Mediterranean climate region site studied by Allen et al., than it is to the desert steppe site studied by Tang et al. (2013). Indeed the latter study even notes that "Where soil pore spaces are filled by water, anoxic conditions increase and CH_4 diffusion to the methanotrophs in the subsurface is restricted."[16] In other words, other conditions being equal, the soil of a region with higher annual precipitation (such as the F&S site) is likely to exhibit a lower rate of CH_4 sequestration than the soil in a region with lower annual precipitation.

Applying CH_4's GWP and Soil Sequestration Rate to the F&S Study

To establish an upper bound for the mass of CH_4 that may be soil sequestered at the F&S site, I will choose the highest rate of sequestration found in the above-cited studies regardless of its region's climatological similarity to the F&S site. That value is 0.0114 Mg ha^{-1} $year^{-1}$ found in desert steppe reported by Tang et al. (2013)—approximately 5.0% of the CH_4 mass produced by the F&S steers.

Subtracting this desert-steppe-site mass from that which is emitted by the steers yields 0.217 Mg CH_4 ha^{-1} $year^{-1}$ (i.e., 0.228 – 0.0114) added to the atmosphere.

With a CH_4 GWP_{20} of 86, the atmospheric CH_4 remaining from the steers per hectare has a CO_2 equivalency of 18.66 Mg CO_2 ha^{-1} $year^{-1}$ (i.e., 86 × 0.217 Mg CH_4 ha^{-1} $year^{-1}$). But the C sequestered by the soil (1.40 Mg C ha^{-1} $year^{-1}$) represents only 5.19 Mg CO_2 ha^{-1} $year^{-1}$ (as C represents only 27% of a CO_2 molecule's mass). On balance, the CH_4 emitted by the steers and the CO_2 contributing to SOC yields a net atmospheric loading equivalent to 13.47 Mg CO_2 ha^{-1} $year^{-1}$ (over a 20-year interval).[17]

Greenhouse Gas Sources Equivalent to the F&S Steers

What other sources might annually produce 13.47 Mg (over a 20-year interval) of atmospheric CO_2 pollution? For answers, I consulted the U.S. Environmental Protection Agency's website[18] which provides a number of possibilities. Among them we find that this quantity of CO_2 is equivalent to consuming 31.3 barrels of oil, or burning 14,370 pounds of coal, or driving an average passenger vehicle 32,302 miles. And this is the air pollution generated by a mere 5.8 steers grazing in accord with the experimental design of F&S on only one hectare of land over the course of approximately two-thirds of a year. This is the prescription these authors tout (p. 28) as an environmentally beneficial land use to be replicated on 13.8 Mha of pasture across the eastern coastal and southeastern states of the U.S. Were such replication to occur, annual CO_2-equivalent pollution of 185,886,000 Mg (over a 20-year interval) would ensue, which the just-cited EPA website equates to the CO_2 pollution annually spewing from more than 54 coal-fired power plants.

Alternate Assumptions of Soil-Depth Measurements and CH_4's GWP Leave Unchanged the Conclusion that F&S Steers are Net Greenhouse Gas Emitters

Although my calculation of CH_4-equivalency to CO_2 has been performed with a value (86) associated with GWP_{20}, were this calculation performed with a value (34) associated with the frequently used GWP_{100}, the atmospheric impact of CH_4 would be reduced but still not be offset by the atmospheric C sequestered by the soil upon which the steers grazed.

For completeness, I'll consider the net C change rates for management under the LGP and UH protocols assessed to the maximum soil depth investigated by F&S (i.e., 150 cm). With the measurements averaged over their three nutrient source treatments, I compute from data in F&S (p. 33, Table 4) an LGP change rate of 0.796 Mg SOC ha^{-1} $year^{-1}$ compared to a UH change rate of 0.28 Mg SOC ha^{-1} $year^{-1}$.[19] Again, as C represents only 27% of the mass of a CO_2 molecule, the LGP value of 0.796 Mg SOC ha^{-1} $year^{-1}$ yields a soil sequestration value of 2.95 Mg CO_2 ha^{-1} $year^{-1}$. When balanced against the CH_4 emitted by the steers, the LGP treatment yields an atmospheric increase in CO_2 equivalency of 16.09 Mg CO_2 ha^{-1} $year^{-1}$ (i.e., 19.04 – 2.95) when the impact of CH_4 is assessed with GWP_{20} at 86.

Consideration of Enteric-Fermentation-Produced CH_4 Leads to New Conclusions about F&S's Study

The CH_4 emitted annually by cattle in F&S's study would generate far more atmospheric heat trapping over a 20-year period than that which would be reduced by the soil sequestration of atmospheric CO_2. Mitigation of global climate change would have been achieved within the experimental design only by foregoing even light grazing (LGP) and instead settling for the lower rate of soil C sequestration afforded by the UH management. This conclusion prevails regardless of whether the change rate of SOC sequestration is measured to a soil depth of 30 or 150 cm, or whether the impact of CH_4 is measured over 20 or 100 years.[20]

Beyond the Domesticated Landscape: Maximizing C Sequestration Depends on the Original Biome

An even more fundamental issue to consider than whether domesticated land, such as that studied by F&S, would better reduce atmospheric greenhouse gases by being grazed or not grazed by cattle is whether the landscape would sequester more atmospheric carbon in its domesticated or in its natural state. Although the region of the F&S test plots has been cropland since the early 19th century, from what sort of biome was that land converted? Was it grassland, similar to the pasture studied in these experiments? Or was the land originally forest? The close proximity (only 16 km distant) of the Oconee National Forest strongly suggests the latter. With sufficient time (and perhaps reforestation) that land would likely revert to forest. And if so, how much atmospheric C might the land then sequester?

That question has been addressed in research reported in Huntington (1995),[21] conducted less than 75 km distant and approximately due west from the site of the F&S experiments. For abandoned cropland regenerating as forest over a 70-year period, Huntington found the rate of soil C sequestration to range from 0.34 to 0.79 Mg ha^{-1} $year^{-1}$ [22] (1.06 to 0.61 Mg ha^{-1} $year^{-1}$ less than results of F&S for LGP management averaged over three nutrient treatments and measured to a depth of 30 cm). But both rates of forest soil C sequestration are certainly superior to net C sequestration of LGP management when CH_4 emissions of the cattle are considered.[23] If the greater goal is to maximize the mass of atmospheric C that is sequestered over a long period, rather than to maximize the rate at which C is sequestered, then additional data from Huntington strongly suggests that regenerating the landscape as native forest is superior to any management of the landscape as pasture.

Consider that in that same regenerating forest, Huntington found 82.1 Mg C ha^{-1} (soil depth 0–100 cm)[24] compared to that of 69.9 Mg SOC ha^{-1} obtained with the best grazing management (i.e., LGP) evaluated by F&S on pasture, averaged over three nutrient treatments to the greater (by 50%) depth of 150 cm (p. 31, Table 2). When above- and below-ground tree biomass was included, the total forest ecosystem sequestration soared to 185 Mg C ha^{-1},[25] more than double the amount stored in F&S's pasture ecosystem that includes C in the below-ground[26] and above-ground biomass[27] annually remaining from the LGP management.

Finally, consider Huntington's report of C sequestration in nearby "mildly disturbed" native forest (Fernback Forest, Atlanta, GA). There, soil C was measured at 122 Mg C ha^{-1}. Carbon in above- and below-ground tree biomass was 203.9 Mg C ha^{-1}, and C sequestered in the total ecosystem was 326 Mg C ha^{-1}.[28] Would managed pasture (that was once native forest, such as that described in F&S) ever sequester C in this amount? Most likely not, as the conversion of a grassland to a coniferous forest (the "Potential Natural Vegetation" of the region) has been estimated to yield an increase within standing biomass of 157.5 MT (equivalently "Mg") C ha^{-1}.[29]

Conclusions

Comparing the findings of F&S to those of Huntington reveals that if the highest objective is to reduce the greenhouse gas impacts of atmospheric C, then forestland should remain undisturbed. Forestland that has become unproductive cropland should be returned to forest if possible, not maintained as pasture. And because the heat-trapping properties of enteric fermentation-emitted CH_4 will far outweigh any benefits associated with increased soil-sequestered C, the least desirable option would be to manage unproductive cropland as cattle-grazed pasture, even under the best grazing management.

Acknowledgments

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Notes

1. Dennis O'Brien, "Cattle Pastures May Improve Soil Quality," *Agricultural Research* (March 2011), http://www.ars.usda.gov/is/ar/archive/mar11/soil0311.pdf (accessed 29 April 2015).
2. Eat Wild, http://www.eatwild.com/environment.html (accessed 12 July 2017).
3. A. J. Franzluebbers and J. A. Stuedemann, "Soil-Profile Organic Carbon and Total Nitrogen During 12 Years of Pasture Management in the Southern Piedmont USA," *Agriculture, Ecosystems and Environment* 129 (2009): 28–36. (All page references in the text refer to this publication unless otherwise stated.)
4. *Wikipedia*, s.v. "Enteric Fermentation," https://en.wikipedia.org/wiki/Enteric_fermentation (accessed 12 July 2017).
5. K. A. Johnson and D. E. Johnson, "Methane Emissions from Cattle," *Journal of Animal Science* 73(8) (1995): 2483–92.
6. Description of "global warming potential" excerpted from *Wikipedia*: "Global warming potential (GWP) is a relative measure of how much heat a greenhouse gas traps in the atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon dioxide. … The GWP depends on the following factors: the absorption of infrared radiation by a given species; the spectral location of its absorbing wavelengths; the atmospheric lifetime of the species." For the full description, see ht tps://en.wikipedia.org/wiki/Global_warming_potential (accessed 9 May 2017).
7. Intergovernmental Panel on Climate Change, *Climate Change 2013: The Physical Science Basis*, 714, Table 8.7, https://www.ipcc.ch/report/ar5/wg1/ (accessed 13 July 2015).
8. Recent research indicates that CH_4's GWP_{20} may be as high as 96. See Thomas Gasser, Glen P. Peters, Jan S. Fuglestvedt, William J. Collins, Drew T. Shindell, and Philippe Clais, "Account-

ing for the Climate-Carbon Feedback in Emission Metrics," *Earth Syst. Dynam.*, 8 (2017): 235–53, doi:10.5194/esd-8-235-2017, http://www.earth-syst-dynam.net/8/235/2017 (accessed 7 May 2017).

9. *Climate Change 2013*, 711.
10. Ibid., 719, Figure 8.32.
11. Robert W. Howarth, "A Bridge to Nowhere: Methane Emissions and the Greenhouse Gas Footprint of Natural Gas," *Energy Science & Engineering*, (2014) doi:10.1002/ese3.35, http://onlinelibrary.wiley.com/doi/10.1002/ese3.35/full (accessed 8 June 2015).
12. Xiaoya Wang, Yingjun Zhang, Ding Huang, Zhiqiang Li, and Xiaoqing Zhang. "Methane Uptake and Emissions in a Typical Steppe Grazing System during the Grazing Season," *Atmospheric Environment* 105 (2015): 14–21.
13. Shiming Tang, Chengjie Wang, Andreas Wilkes, Pei Zhou, Yuanyuan Jiang, Guodong Han, Mengli Zhao, Ding Huang, and Philipp Schönbach. "Contribution of Grazing to Soil Atmospheric CH_4 Exchange During the Growing Season in a Continental Steppe," *Atmospheric Environment* 67 (2013): 170–76.
14. Tang et al. (2013), Table 2, p. 175.
15. D. E. Allen, D. S. Mendham, Bhupinderpal-Singh, A. Cowie, W. Wang, R. C. Dalal, and R. J. Raison, "Nitrous Oxide and Methane Emissions from Soil are Reduced Following Afforestation of Pasture Lands in Three Contrasting Climatic Zones," *Australian Journal of Soil Research* 47(5) (2009): 443–58.
16. Tang et al., "Contribution of Grazing," (2013): 175.
17. In this and subsequent calculations of net atmospheric C-based greenhouse gases due to the F&S steers (and the land upon which they graze), I have attempted to bias the results in favor of graziers by subtracting from the steer-emitted CH_4 a reasonable upper bound estimate of the rate at which CH_4 is sequestered by the soil. If the value chosen is truly greater than the rate at which CH_4 is actually sequestered by the soil in the F&S study, my approach will be grazier biased regardless of whether the method used by F&S to measure the rate of soil C sequestration accounted for sequestered C derived from atmospheric CH_4.
18. United States Environmental Protection Agency, "Greenhouse Gas Equivalencies Calculator—Calculations and References," https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references (accessed 29 April 2017).
19. The lower change rates of SOC to depth of 150 cm relative to 30 cm result from a small but significant decline in SOC with depth below 30 cm. The authors suggest a few possible causes for this phenomenon, but none can be accepted with certainty.
20. For a 100-year time frame with CH_4's GWP_{100} at 34, F&S's steer-emitted CH_4 yields a CO_2 equivalency of 7.514 Mg ha^{-1} $year^{-1}$. The soil-sequestered atmospheric C (C being 27% of CO_2's mass) to soil depth of 30 cm (under LGP management averaged over three nutrient treatments as reported in Table 4, p. 33) being 5.19 Mg ha^{-1} $year^{-1}$ results in an atmospheric CO_2 equivalency gain of 2.324 Mg ha^{-1} $year^{-1}$ (i.e., 7.514 Mg ha^{-1} $year^{-1}$ - 5.19 Mg ha^{-1} $year^{-1}$). If the atmospheric C sequestered by the soil is considered to soil depth of 150 cm, then CO_2 removed from the atmosphere (under LGP management averaged over three nutrient treatments as reported in Table 4, p. 33) is 2.95 Mg ha^{-1} $year^{-1}$, yielding an atmospheric CO_2 equivalency gain of 4.564 Mg ha^{-1} $year^{-1}$ (i.e., 7.514 Mg ha^{-1} $year^{-1}$ - 4.564 Mg ha^{-1} $year^{-1}$).

    An article more recent than F&S but of similar nature is Megan B. Machmuller, Marc G. Kramer, Taylor K. Cyle, Nick Hill, Dennis Hancock, and Aaron Thompson, "Emerging Land Use Practices Rapidly Increase Soil Organic Matter," *Nat. Commun.*, (2015) doi:10.1038/ncomms7995, http://www.nature.com/ncomms/2015/150430/ncomms7995/abs/ncomms7995.htm (accessed 26 July 2015). Machmuller et al. examined the conversion of Georgia cropland to dairy pasture, but unlike F&S, accounted for CH_4 emissions from the ruminant animals (cows, in this case) that grazed the land.

Machmuller et al. performed a "whole farm C sequestration calculation" based upon the method reported in Jeff B. Belflower, John K. Bernard, David K. Gattie, Dennis W. Hancock, Lawrence M. Risse, and C. Alan Rotz, "A Case Study of the Potential Environmental Impacts of Different Dairy Production Systems in Georgia," *Agricultural Systems* 108(C) (2012): 84–93 that used a CH_4 GWP_{100} of 25 (based on the IPCC 2007 document, *Climate change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf [accessed 26 July 2015]). Based on that analysis, Machmuller et al. report that the farms they studied would be net C sinks for "at least an initial 5-year period following land use change." Had the Machmuller et al. study been performed with the CH_4 GWP_{20} of 86 (based on the more recent report by the IPCC, *Climate Change 2013: The Physical Science Basis*, 714, Table 8.7, https://www.ipcc.ch/report/ar5/wg1/ [accessed 26 July 2015]) their claimed 5-year period as a net C sink would certainly have been reduced, if not eliminated. But even under the best case scenario acknowledged by Machmuller et al., the dairy operations under study would not be sustainable over the long term with regard to greenhouse gas emissions.

21. Thomas G. Huntington, "Carbon Sequestration in an Aggrading Forest Ecosystem in the Southeastern USA," *Soil Science Society of America Journal* 59(5) (1995): 1459–67.
22. "Carbon Sequestration," p. 1463.
23. Even the Huntington (1995) lower value for forest soil C sequestration (i.e., 0.34 Mg ha^{-1} $year^{-1}$) is superior to F&S's LGP management which produces net atmospheric greenhouse gas loading equivalent to 12.3 Mg CO_2 ha^{-1} $year^{-1}$ (CH_4 GWP_{20} at 86) or 0.634 Mg CO_2 ha^{-1} $year^{-1}$ (CH_4 GWP_{100} at 34).
24. "Carbon Sequestration," p. 1463, Table 1.
25. Ibid.
26. F&S do not report the weight of below-ground biomass of their forage (i.e., Coastal Bermuda Grass) in LGP management, but note that their soil samples included roots (p. 30). Other research has estimated below-ground temperate grassland biomass at only 6.3 metric tons (MT) ha^{-1} (equivalently 6.3 Mg ha^{-1}) which provides an upper bound on the quantity of sequestered C. See T. M. Sobecki, D. L. Moffitt, J. Stone, C. D. Franks, and A. G. Mendenhall, "A Broad-Scale Perspective on the Extent, Distribution and Characteristics of U.S. Grazing Lands," in *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect*, ed. R. F. Follett, J. M. Kimble, and R. Lal (Boca Raton, Florida, Lewis Publishers, 2001), 44, Table 2.4.
27. F&S report that the LGP management includes leaving 3 Mg ha^{-1} of forage, mostly Coastal Bermuda Grass. As this grass consists of approximately 44.6% C by weight (as calculated from data presented in "Broad-Scale Perspective," p. 53; see Note 26 above for details), the above-ground annual residual vegetation sequesters, at most, 1.34 Mg C ha^{-1}.
28. "Carbon Sequestration," p. 1463.
29. T. M. Sobecki, D. L. Moffitt, J. Stone, C. D. Franks, and A. G. Mendenhall, "A Broad-Scale Perspective on the Extent, Distribution and Characteristics of U.S. Grazing Lands," in *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect*, ed. R. F. Follett, J. M. Kimble, and R. Lal (Boca Raton, Florida, Lewis Publishers, 2001), 49, Table 2.5.