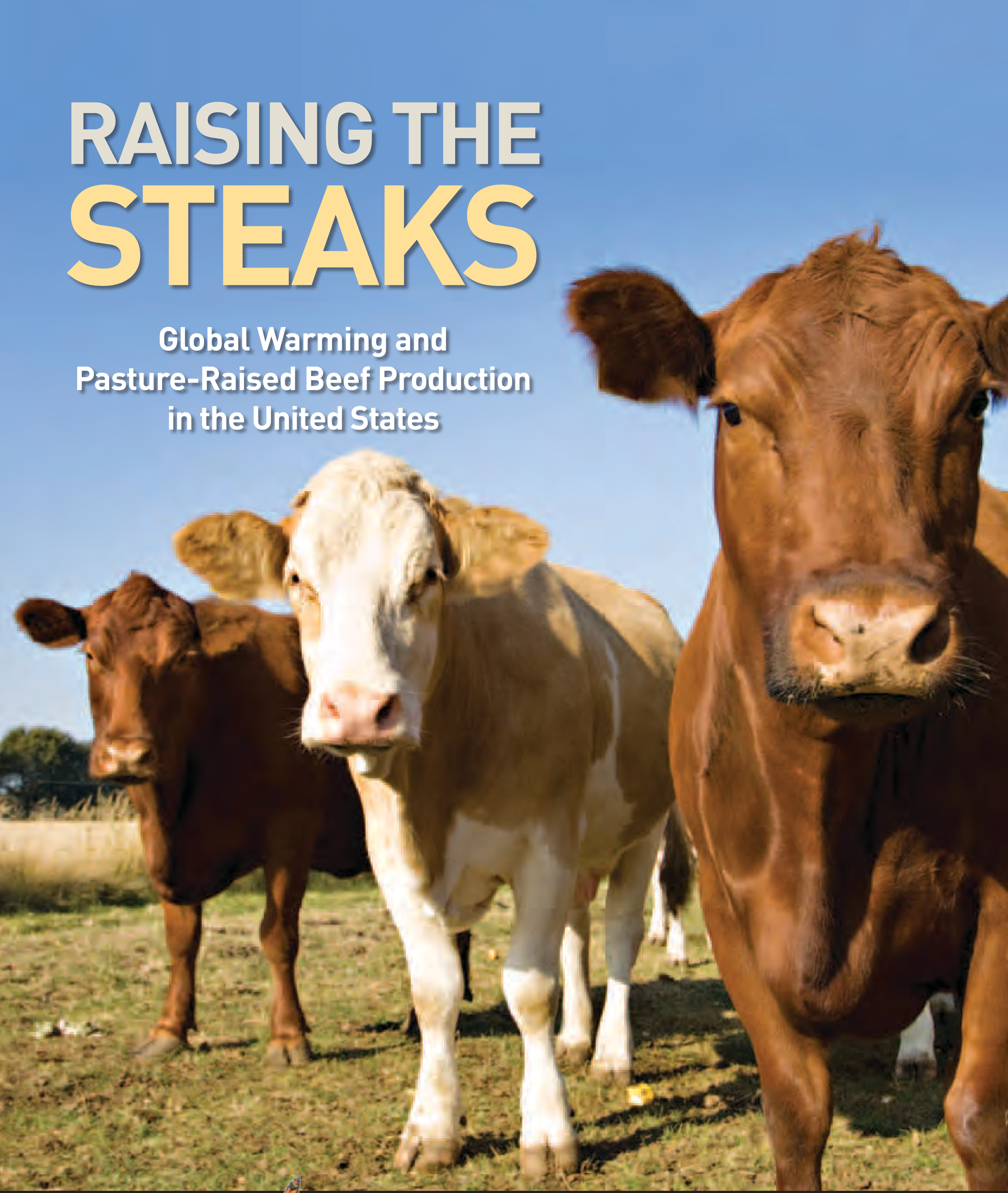
RAISING THE STEAKS

Global Warming and Pasture-Raised Beef Production in the United States



Union of Concerned Scientists

Citizens and Scientists for Environmental Solutions

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Global Warming and Pasture-Raised Beef Production in the United States

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Union of Concerned Scientists
Citizens and Scientists for Environmental Solutions

FEBRUARY 2011

Doug Gurian-Sherman is a senior scientist in the Food and Environment Program of the Union of Concerned Scientists (UCS).

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This report is dedicated to the memory of James Liebman, steadfast friend and mentor. His advice regarding the challenges of livestock production deeply affected my thinking.

Executive Summary

N. Wade Snyder USDA-ARS

Emissions of two important heat-trapping gases from agriculture account for about 6 percent of total global warming emissions in the United States, according to the U.S. Environmental Protection Agency. Beef production contributes about a third of those emissions, or roughly 2.2 percent of the total. Livestock contribute a greater share of global warming emissions in parts of the world with lower industrial emissions—about 18 percent, according to one estimate, including contributions from deforestation driven by livestock production.

Agriculture emits all three major greenhouse gases—methane, nitrous oxide, and carbon dioxide—but the latter is a small part of the total in the United States and is not considered in this report.

Beef cattle and stored cattle manure are responsible for 18 percent of U.S. methane emissions—which have 23 times the warming effect of carbon dioxide emissions. Methane from beef cattle accounts for about 1.4 percent of combined U.S. heat-trapping emissions.

The Union of Concerned Scientists estimates that beef cattle produce roughly another 0.8 percent of U.S. global warming emissions in the form of nitrous oxide—which has about 296 times the warming effect of carbon dioxide. Nitrous oxide is produced in growing grains used to feed beef cattle in CAFOs (confined animal feeding operations), from pasture, and from stored manure.

All beef cattle spend the first months of their lives—and sometimes more than a year—on pasture or rangeland, where they graze on forage crops such as grass and alfalfa. While some continue to live and feed on pasture until slaughter, most U.S. beef cattle are fattened, or "finished," for several months in CAFOs, where they eat grain rather than forage.

This report evaluates the prospects for changing management practices to reduce the climate impact of the time beef cattle spend on pasture or rangeland. Improved practices are most readily applied to the finishing stage of fully pasture-raised systems—a growing alternative to CAFOs, given research showing that pasture finishing has nutritional and environmental benefits. But such practices could also apply to the range portion of a CAFO system.

This report shows that use of practices that reduce methane and nitrous oxide emissions from beef production would have a measurable although relatively small impact on the U.S. contribution to climate change.

However, pasture plants can remove carbon dioxide from the atmosphere and store—or sequester—it in soil, further reducing the climate impact of beef production. And in the long term, the use of climate-friendly best practices in the United States may lead to substantial cuts in global warming emissions if adopted in countries where beef production accounts for a greater share of those emissions.

Practices that reduce heat-trapping emissions and boost carbon sequestration also typically curb other important environmental harms from pasture beef production. For example, excess nitrogen—the source of nitrous oxide emissions—from pastures, CAFOs, and crops used to feed beef cattle in CAFOs pollutes air and water, acidifies soils, reduces biodiversity, and shrinks Earth's protective stratospheric ozone layer. The environmental benefits of practices that reduce the climate impact of pasture beef are another important reason to adopt them.

Key Findings

Major findings of this report include:

The use of pasture management practices that improve the nutritional quality of forage crops could reduce methane emissions from pasture beef by about 15 to 30 percent. However, some grazing lands would not benefit from these practices, so overall reductions in U.S. global warming emissions would be considerably less than 0.5 percent—or one-third of the 1.4 percent of emissions that now come from beef production by applying these practices where appropriate.

The use of better management practices on pastures that have not been well managed, or the conversion of crop acres to pasture, could allow pastures to sequester about 0.8 to 1.0 metric ton of carbon per hectare. Better management practices on pasture could offset 0.1 to 2 percent of annual U.S. heat-trapping emissions, depending on which practices land managers adopt. Converting croplands to pasturelands could increase that amount, but new practices may involve tradeoffs in heat-trapping gases that need to be considered.

In many areas, soil could continue to add carbon for several decades—until the rate at which soil loses carbon equals the rate at which it accumulates. Land managers must sustain the practices they use to enhance carbon sequestration, or soil could release the stored carbon back into the atmosphere.

Best management practices used to grow crops, such as no-till methods for corn used in beef CAFOs, sequester about only half as much carbon as well-managed pasture. And only about 20 to 25 percent of U.S. corn acres now rely on no-till farming—a practice often linked to greater carbon sequestration.

Best management practices available now that can reduce the climate change impact of pasture beef include:

- Increasing the percentage of legumes in forage mixtures, which improves their nutritional quality and thus reduces methane emissions from cattle digestion.
- Avoiding excessive use of nitrogen fertilizer to curb nitrous oxide emissions.
- Using moderate stocking densities (the number of cattle per acre) to avoid excessive manure buildup and thus methane and nitrous oxide emissions, and to allow pastures to recover from grazing.
- Avoiding the use of low-quality, mature pasture crops to graze cattle.
- Preventing overgrazing to increase carbon sequestration in pasture soils.

Other innovative practices that may have climate benefits include:

- Breeding better pasture species to improve the nutritional quality of pasture forage. Higher-quality forage could reduce methane and nitrous oxide emissions by accelerating cattle growth and allowing cattle to use the nitrogen and carbohydrates in forage more efficiently.
- Planting birdsfoot trefoil in pastures. This legume produces beneficial condensed tannins—compounds that may reduce methane and possibly nitrous oxide emissions.
- Moving water and shelter sources to ensure that manure from grazing cattle is spread more evenly on pastures, reducing methane and nitrous oxide emissions.

Most U.S. beef cattle today spend several months in CAFOs (confined animal feeding operations), which can fatten cattle more quickly than pasture but are characterized by crowded conditions and the production of unmanageable amounts of waste.

- Using nitrification inhibitors—chemicals that prevent the microbial processes that change ammonia to nitrous oxide—to reduce nitrous oxide emissions from urine patches.

Further research is needed to better quantify the cuts in global warming emissions from all these practices. Several other practices that optimize grazing and pasture growth—including managed rotational grazing, which entails moving grazing cattle among fenced pasture areas frequently—seem promising but also require more research. And the possible synergies of integrating several promising practices would particularly benefit from further analysis.

Smart Pasture Operations versus CAFOs

Studies have come to different conclusions about the climate impacts of pasture beef finishing and CAFO systems. Analysts often do not have enough information to accurately compare these types of beef production. Variations in pasture management practices and local conditions can alter the outcomes of such comparisons—as can the assumptions analysts make. For example, the climate impact of pasture finishing versus CAFOs varies depending on how quickly pasture soils accumulate carbon.

The rate at which cattle gain weight has a large impact on the global warming emissions of beef on a per-pound basis, with implications for comparisons of production systems. The high-starch feeds used in CAFOs enable cattle in those systems to gain weight more rapidly and efficiently than cattle that feed on pasture forage, and with fewer calories lost to methane emissions. Across nine studies, for example, the average weight gain of cattle eating forage was 76 percent that of cattle eating a grain-based diet. Slower weight gain also means that cattle produce methane and nitrous oxide emissions for a longer period of time.

However, the dietary efficiency of forage can vary greatly. One study showed cattle grazing on poor-quality forage gained weight just 27 percent as quickly as cattle eating grain-based feed used in CAFOs, while other studies showed similar weight gain rates for high-quality forage and grain-based feed.

In one recent study, cattle in Iowa eating forage gained 0.6 kilogram (kg) per day, while the average from nine studies of cattle forage was 1.03 kg per day—72 percent greater efficiency. Given the higher forage efficiency values in some studies, it appears that adopting available practices that improve forage quality could minimize the climate emissions advantage of grain.

Well-managed perennial pastures generally sequester more carbon than row crops such as corn, offsetting the feed efficiency of CAFOs. Growing the grain fed to cattle in CAFOs also produces global warming emissions, which should be taken into account when comparing pasture finishing and CAFOs.

Land productivity also affects the climate impact of beef production, and thus any comparison between the two systems. Fertile soil allows higher productivity of pasture forage and grain—and thus beef—per unit of land than poor soil. Higher pasture productivity also increases the potential amount of biomass—forage and manure—that soil can store as carbon.

Most U.S. feed grain crops are grown on higher-quality land than that used for most pasture beef production. Analyses that overlook differences in land quality may underestimate the potential for reducing the climate impact of pastures compared to CAFOs.

Recommendations

The federal farm bill and other policy mechanisms offer substantial opportunities to reduce the climate change impact of pasture beef production. The following recommendations would improve our understanding of the potential for best practices to curb the heat-trapping emissions and boost the carbon sequestration of pasture beef, and spur the use of those practices:

1. The U.S. Department of Agriculture (USDA) should expand its research on global warming emissions from pasture beef production, and further develop management practices to curb those emissions. Critical needs include:

- Breeding and development of other practices to promote more nutritious pasture crops.
- Investigating the most effective combinations of climate-friendly practices.
- Improving the ability of high-quality legumes to become established and to persist in mixed pastures.
- Improving the efficiency with which pasture crops use nitrogen.
- Boosting forage yields and extending the period of high-quality pasture growth.
- Collecting information on practices now used to manage the quality of pastures and the amount of carbon in various soils.
- Optimizing intensive rotational grazing systems and investigating their impact on methane and nitrous oxide emissions and long-term carbon sequestration.
- Pursuing whole-farm studies of suites of climate-friendly practices to identify synergies, optimize carbon budgets, and evaluate any tradeoffs.
- Developing demonstration projects and educational materials to alert cow-calf operators and pasture beef producers to the advantages of better pasture management.

2. The USDA's Natural Resources Conservation Service should expand its efforts to encourage best management practices that reduce methane and nitrous oxide emissions and boost carbon sequestration. This work should include:

- Using the Conservation Stewardship Program to provide incentive payments for:
  - Practices that may reduce methane and nitrous oxide emissions, including increasing the share of legumes and improved forage crops in forage mixtures, using moderate cattle stocking densities, using appropriate amounts of synthetic fertilizer, avoiding grazing cattle on low-quality mature pasture—such as by substituting high-quality stored forages—and encouraging more even distribution of manure on pastures.
  - Practices that increase carbon sequestration, such as supplying the precise amount of nutrients that crops need from legume species, manure, or synthetic fertilizer, and preventing overgrazing.
- Providing technical assistance to beef producers to help and encourage them to implement such practices.
- Providing transitional support through the Environmental Quality Incentives Program to beef producers that switch from confinement to pasture-based finishing systems that use best management practices.

3. State- and federally funded univer-sity extension services should advise and train beef producers on climate-friendly practices, including use of the highest-quality forage, and strategies to prevent overgrazing.

CHAPTER 1

Why Focus on Beef?

Beef production is a major U.S. industry, delivering about 94 million head of cattle with a retail value of $73 billion in 2009 (USDA 2010c). Beef accounts for more global warming emissions in the United States than the production of other foods (Eshel and Martin 2006). This report evaluates the potential for pasture beef producers to curb the industry's contribution to climate change by adopting better management practices.

A better burger would be no small achievement. U.S. agriculture accounts for about 6 percent of U.S. global warming emissions, according to the U.S. Environmental Protection Agency (EPA 2010). (Like this report, the EPA considers methane and nitrous oxide emissions but excludes carbon dioxide emissions.) Although the climate change impact of other economic sectors such as transportation and power plants dwarfs that of agriculture, beef production nevertheless offers an opportunity to curb a small, but measurable, amount of U.S. heat-trapping emissions.

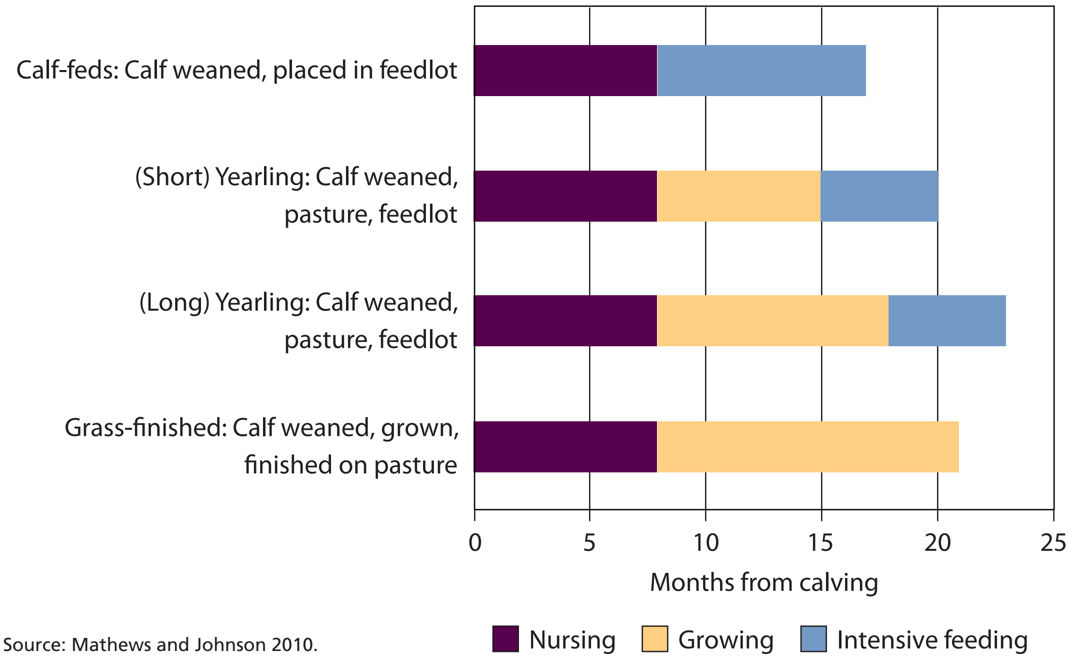
Beef cattle contribute to climate change chiefly through emissions of two potent global warming gases: methane and nitrous oxide. Methane has about 23 times the global warming potential of carbon dioxide, while nitrous oxide is about 296 times as potent.

The digestive system of cattle is especially effective at generating large amounts of methane. Methane forms primarily when feed ferments in the rumen, or fore-stomach, in a process known as enteric fermentation.

Stored manure releases methane emissions when it becomes anaerobic (lacking oxygen), although these emissions are much more modest than those from enteric

FIGURE 1. Timelines for Cow-Calf and Pasture Beef Finishing

As this graph demonstrates, all beef cattle spend considerable time on grasslands (pasture or range). Only the blue bars represent the time grain-fed beef cattle spend in CAFOs.



Source: Mathews and Johnson 2010.

fermentation. Most nitrous oxide emissions from beef production stem from the nitrogen added to feed crops or pasture as chemical fertilizer, manure, or legume crops.

Enteric fermentation from beef cattle accounts for about 24 percent of global warming emissions from U.S. agriculture, and 52 percent of all U.S. methane emissions (EPA 2010). Manure management from beef cattle accounts for another 2 percent of heat-trapping emissions from U.S. agriculture.[1]

Today most U.S. beef cattle are produced through "cow-calf operations." That is, they spend the first part of their lives grazing on rangeland or pasture, or nursing on cows that graze. The cattle are then fattened, or finished, in CAFOs (confined animal feeding operations)—also known as feedlots. Beef cattle typically spend 8 to 16 months on pasture or range before finishing in CAFOs for 4 to 8 months (Figure 1) (Mathews and Johnson 2010).

CAFOs cannot replace cow-calf operations because cattle fed a grain-based diet for too long develop severe health problems, such as acute or chronic acidosis, which leads to liver abscesses and other serious maladies (Owens et al. 1998). Feeds formulated for CAFOs, known as concentrate, are therefore usually 10 to 15 percent forage or other roughage, although this cannot eliminate health problems in the long run.

Cattle grazed on range and pastureland—both those destined for finishing in CAFOs and those that are entirely pasture-raised—require substantial resources. Some 26 percent of U.S. agricultural land area—51 million hectares (126 million acres)—is devoted to pasture and range, and beef and dairy cattle are the main users of those lands (Follette, Kimble, and Lal 2001). Some 35 percent of all U.S. land area is devoted to grazing if the total includes pasture that alternates with row crop production and grazed forestland (Lubowski et al. 2002).

Cattle finished in CAFOs require large amounts of grain and limited resources such as water. About half of U.S. corn and soybeans, nearly all U.S. alfalfa production, and significant proportions of crops such as sorghum and barley are devoted to feeding livestock, with a substantial amount attributable to beef cattle. Substantial amounts of corn stover (stalks and leaves) are also used for cattle forage or silage (Gurian-Sherman 2008).

Beef production also exerts other major effects on the environment. Livestock, including cattle, produce about 50 percent of airborne ammonia in the United States.

1 Manure management refers only to the storage of manure. Emissions from manure deposited directly on pasture by cattle or spread onto land from manure storage facilities are counted under soil management.

That, in turn, contributes to air pollution, acid soils, reduced biodiversity, and—along with nitrate leaching—eutrophication (dead zones) in the Gulf of Mexico and other estuaries (EPA 2005; Anderson, Strader, and Davidson 2003; Goolsby et al. 1999).[2]

This report focuses on grazed beef cattle because all spend some time on pasture or rangeland, and because better management practices could curb methane and nitrous oxide emissions from the pasture portion of beef production substantially. Better management practices can also enable pasturelands to remove—or sequester—substantial amounts of carbon dioxide from the atmosphere, and store it for long periods. Adoption of these practices on rangeland, where possible, can also reduce global warming emissions and sequester carbon.

Some analysts have proposed "smart" pasture operations—in which cattle graze their entire lives on well-managed pastures, consuming grasses and legumes such as alfalfa—as a more environmentally friendly alternative to the CAFO system. This report takes a careful look at ways to reduce the climate impact of such "pasture finishing," as well as of the pasture segment of CAFO operations.

Fortunately, practices that reduce nitrous oxide and methane emissions from beef production and sequester carbon in pasture soils also curb the industry's other environmental effects. And as U.S. beef producers adopt these climate- and environment-friendly practices, they will serve as a model for countries where agriculture accounts for a larger share of global warming emissions. Pasture beef has the additional benefit of lower saturated fat content and a higher proportion of omega-3 fatty acids, both of which are associated with health benefits (Clancy 2006).

Organization and Focus of This Report

Chapter 2 explores the contribution of beef cattle to U.S. global warming emissions in more depth. Chapter 3 then examines the sources of methane emissions from beef cattle, and practices that may curb those emissions. That chapter also considers practices that enable beef cattle to use feed or forage more efficiently, and therefore gain weight faster—which can reduce both methane and nitrous oxide emissions.

Chapter 4 focuses on nitrous oxide emissions from pastures, and practices that could cut those emissions. Chapter 5 reviews the potential for pasture to sequester carbon.

Chapter 6 compares the climate change impact of pasture and CAFO finishing given best management practices. That analysis is important because agricultural policy

2 Most of the nitrogen that causes the dead zone in the Gulf of Mexico comes from fertilized croplands. However, roughly half of the major grain crops produced in the United States are used to feed livestock, including about 20 percent of corn used to feed beef cattle in CAFOs.

and consumer demand could spur beef producers in the United States to shift finishing systems, and producers, consumers, and policy makers need to consider the climate change impact of such a shift. Our comparisons of CAFOs and pasture are not meant to be comprehensive, but are intended to highlight important parameters that are not often evaluated. The final chapter summarizes the report's findings and proposes policy recommendations.

Overall, the report focuses on mitigation practices that can be and sometimes are used now, and that could produce significant environmental benefits if more widely adopted. The report also suggests how to improve those practices. The report does not consider techniques that could be useful but have not yet found commercial application, such as the use of vaccines to curb methane-producing microbes, or chemicals that reduce protozoa in cattle rumen (defaunation). Cattle genetics and breeding may have a substantial impact on global warming emissions, but is at an early stage of evaluation by scientists, and is not evaluated in this report.

The report also does not examine several controversial practices that *have* found widespread application, such as the use of growth hormone and antibiotics to promote cattle growth. However, this report does consider average daily weight gain of feedlot cattle, which partly accounts for those practices.

The report also does not consider the direct or indirect use of fossil fuel in beef production. Although tilling soil and producing and applying nitrogen fertilizer and pesticides produce carbon dioxide emissions, those emissions are less important than methane and nitrous oxide emissions from agriculture.

Eating less beef by substituting the consumption of other foods may also reduce global warming impacts, but is beyond the scope of this report.

Methodology

To evaluate the climate change impact of pasture beef, we searched online databases for studies of pasture beef and pasture dairy production. Our analysis included some dairy research because information on pasture beef finishing was not always available for all topics. Differences in metabolism between lactating and non-lactating dairy cows and rapidly growing beef cattle are important, and analyses of heat-trapping emissions from dairy cows cannot be directly applied to beef cattle. However, the basic processes and biology are similar enough that studies of dairy cows can shed light on general principles.

This report does not focus primarily on modeling because we wanted to explore best practices in detail. Models are important, but they may overlook the complexities of working farms, which may differ considerably from the conditions that modelers assume. We cite findings from modeling studies primarily to illustrate their limitations.

These limitations relate primarily to scale. Existing climate models are most useful in illustrating the impact of particular practices or combinations of practices at a regional or larger scale. Although analysts can also apply these models to conditions at the farm level, it is often not practical to do so.

What's more, while scientists understand the basic biological processes that give rise to heat-trapping emissions from beef production reasonably well, gaps remain, and modeling results can obscure those gaps.

This report focuses on practices that can mitigate heat-trapping emissions or boost the carbon sequestration of beef production—or that show promise of doing so. The goal is to ensure that promising practices that may not be captured by modeling exercises remain on the policy map and research agenda.

CHAPTER 2

The Impact of Beef Production on Climate and the Environment

U.S. global warming emissions totaled 7,150 million metric tons (MMT) of CO_2 equivalent in 2007 (EPA 2007). Methane emissions from beef cattle digestion total 100.8 MMT of CO_2 equivalent, while methane emissions from manure stored in feedlots and other facilities total 2.5 MMT of CO_2 equivalent (EPA 2010). Methane from beef cattle therefore accounts for about 1.4 percent of U.S. global warming emissions.

The share of nitrous oxide emissions from beef cattle in total U.S. global warming emissions is more difficult to determine. That is because those emissions stem from several sources, some of which are not readily quantified. Here, an estimate of nitrous oxide from corn grown to feed beef cattle in CAFOs is added to an estimate of nitrous oxide production from beef cattle on grasslands to give a rough estimate of nitrous oxide from beef production in the United States.

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In addition to contributing to global warming, waste-intensive CAFOs such as this one, as well as poorly managed pasture operations, can have major impacts on water and air quality.

Nitrous oxide emissions from corn used to feed beef cattle are calculated as follows. The United States produced 26 billion pounds of beef in 2009 (based on carcass weight) (USDA ERS 2010c). Each pound of beef requires about seven pounds of feed (Goodland 1997), which is usually 80 to 85 percent corn. That means beef producers fed about 155 billion pounds of corn—or 20 percent of all corn production—to U.S. cattle in 2009. The area used to grow that corn totaled 16.8 million acres.[3]

U.S. farmers apply an average of 62.7 kg (138 pounds) of nitrogen fertilizer to each acre used to grow corn (USDA ERS 2010a). According to the Intergovernmental Panel on Climate Change, about 1 percent of applied nitrogen is lost as direct nitrous oxide emissions (IPCC 2006).[4] The amount of nitrogen directly converted to nitrous oxide in growing corn for beef fattened in CAFOs is therefore about 10.4 million kg. If we take into account the mass of oxygen in nitrous oxide, fertilizer applied to corn acres used to feed U.S. beef cattle results in 14.2 million kg of nitrous oxide emissions.

About 30 percent as much nitrous oxide is released from cropland indirectly—for example, after nitrate leaches into groundwater—as from direct conversion of applied nitrogen (EPA 2010). When we add data on this indirect source of nitrous oxide to data on direct sources, the nitrous oxide emissions from corn fed to beef cattle total

3 The area used to grow this corn is based on corn yields that averaged 165 bushels per acre in 2009–2010, and each bushel has 56 pounds of corn (USDA ERS 2010b). Alternatively, corn used by CAFO beef cattle in the United States can be estimated from the amount needed per head—typically about 50 to 70 bushels—multiplied by the number of head of cattle. This calculation gives a somewhat smaller amount of corn used by CAFOs than our estimate above.

4 The nitrous oxide direct emission factor has substantial uncertainty, with a confidence interval from 0.3 to 3 percent.

about 18.5 million kg—or 5.76 MMT of CO_2 equivalent. That accounts for about 0.08 percent of total U.S. global warming emissions.

Jeff Vanuga, USDA-NRCS

A substantial share of U.S agricultural grasslands are devoted to beef production, with lesser amounts used for dairy cows, and small amounts for sheep, goats, horses, and other livestock. For example, the 22 western states that account for the majority of U.S. cow-calf operations devoted 75 percent of pasture and rangeland primarily to beef (Conner et al. n.d.). Given EPA estimates of nitrous oxide emissions from grasslands (52.1 and 9.6 MMT of CO_2 equivalent for direct and indirect emissions), these lands produce 46.28 MMT—or 0.6 percent—of U.S. global warming emissions. Stored beef manure produces another 7.4 MMT of CO_2 equivalent of nitrous oxide emissions (EPA 2010)—or about 0.1 percent of U.S. global warming emissions.

Nitrous oxide emissions from U.S. beef production therefore account for about 0.8 percent of all U.S. global warming emissions. That estimate does not account for emissions from the substantial amount of forage crops—especially alfalfa—harvested to feed cattle. Much of the 23 million acres used to produce forage provide feed for dairy cows, but a substantial amount also feeds beef cattle. This total also does not account for other crops that compose a small proportion of grain feed for beef cattle, such as soybean meal, sorghum, and other grains. However, these sources contribute a much smaller share of nitrous oxide emissions from beef production than grasslands and corn.

In sum, beef cattle produce roughly 2.2 percent of U.S. global warming emissions, and about a third of the direct global warming emissions from U.S. agriculture. Much of these emissions stem from cow-calf operations and CAFOs, because pasture beef finishing accounts for a very small percentage of U.S. beef finishing. However, pasture finishing is expanding, so evaluating its impacts and potential for curbing its heat-trapping emissions is important.

Mitigating the Climate Impacts of Beef Production: How Big an Effect?

As Chapter 3 shows, management practices available now could reduce methane emissions from the digestion of pastured beef cattle by 15 to 30 percent, and probably more if used in combination. If applied to all U.S. pasture and cow-calf operations, those practices would curb U.S. global warming emissions by less than 0.5 percent.

Some managers are already using some of these practices on pastures, and applying them to other pastures—such as rangeland used for cow-calf operations—may not be cost-effective. What's more, given the small contribution of nitrous oxide emissions from beef production, practices that reduce the latter would curb U.S. global warming emissions by only a small amount. Thus the practical impact of improved practices on U.S. pasture and rangeland devoted to beef cattle is probably considerably less than 0.5 percent of U.S. global warming emissions.

Land management practices that sequester carbon in pasture soils probably offer the most significant opportunity to reduce the climate impact of U.S. beef production. U.S. grazing lands could sequester 5 to 142 MMT of carbon, depending on the practices, according to one estimate (Ogle, Connant, and Paustian 2004). That stored carbon would offset 0.1 to 2 percent of annual U.S. global warming emissions. However, that analysis does not consider the additional carbon sequestration that could occur if land managers shifted some crop acres now devoted to beef feed to well-managed pasture. Still, land can sequester large additional amounts of carbon only for several decades, and these gains are reversible if land managers do not sustain the improved practices.

Better pasture management practices would have a larger impact on heat-trapping emissions if used worldwide. For example, a recent U.N. report estimates that livestock account for 18 percent of global heat-trapping emissions (Steinfeld et al. 2006). Nitrous oxide and methane account for about 11 percent of those emissions (calculated from Steinfeld et al., Table 3.12). Most of the remaining 7 percent of livestock emissions comes from deforestation linked to livestock production.

Methane from livestock digestion—mainly in cattle but also in sheep and goats—accounts for 4.5 percent of global heat-trapping emissions (Steinfeld et al. 2006). Because cattle production is less efficient in many parts of the world than in the United States, these regions can likely make more of an impact on these emissions by adopting better pasture practices. Other regions also have substantial opportunities to increase carbon sequestration in agricultural soils.

Other Environmental Impacts of Pasture Beef

Livestock produce significant environmental effects beyond global warming emissions (Rockstrom et al. 2009). Fortunately, practices that reduce the climate change impact of beef production can often also reduce other types of pollution.

Oversupply of nitrogen and phosphorus from manure and fertilizers applied to pastureland and feed crops pollutes water and air, acidifies soil, reduces biodiversity, and degrades land. For example, livestock manure is the major source of airborne ammonia, which acidifies soil when it precipitates and also reduces biodiversity.

Nitrate and phosphorus also pollute groundwater and surface water when they escape from pastures, CAFOs, or crop fields. That, in turn, reduces biodiversity in streams, rivers, and lakes, and contributes to coastal dead zones. Nitrate pollution in groundwater and surface waters is also a health hazard.

Improperly managed livestock also cause soil erosion and reduce its fertility, and use significant quantities of water (Gurian-Sherman 2008; Steinfeld et al. 2006). Given curbs on the use of chlorofluorocarbons, nitrous oxide may now be the most important factor in depletion of stratospheric ozone (Ravishankara, Daniel, and Portmann 2009). These and other harms from livestock and beef production may be even more important than their climate consequences (Rockstrom et al. 2009, Vitousek et al. 2009).

Fortunately, most practices that curb the climate impact of pasture beef production also reduce its broader environmental harm. For example, growing and breeding more nutritious pasture forage improves cattle digestion, reducing methane emissions. More nutritious forage also allows cattle to grow more quickly, so they spend less time producing manure, which contributes to nitrogen and phosphorus pollution.

Forage that allows more efficient use of protein—the main source of nitrogen in crops—could reduce the amount of nitrogen per pound of beef that ends up in water or air. Pasture crops bred to use nitrogen more efficiently could also reduce nitrogen pollution. Boosting soil carbon sequestration rates, meanwhile, usually increases the organic matter in soil, which in turn improves fertility and water-holding capacity. And that improves crop productivity and reduces drought stress and the need for irrigation.

Integrated livestock-crop farms that include pasture have recorded improvements in several environmental measures. These include better water quality owing to reduced erosion and sediment, greater biodiversity, and reduced nitrogen and phosphorus pollution in water (Russelle, Entz, and Franzluebbers 2007; Boody et al. 2005; Burkart et al. 2005; Rotz et al. 2005).

Summary: The Impact of Beef Production on Climate and the Environment

Beef production accounts for about 2.2 percent of U.S. global warming emissions. About 1.4 percent stems from enteric fermentation from beef cattle alone—much from cow-calf operations, but some from pasture finishing and CAFOs. Better pasture practices could reduce this impact by less than a third. Practices that increase carbon sequestration in U.S. grassland soils can curb another 0.1 to 2 percent of U.S. global warming emissions.

Together these improvements could reduce U.S. global warming emissions by up to (but probably less than) 2.5 percent. Because nitrous oxide emissions from beef production account for only about 0.8 percent of U.S. global warming emissions, the impact from reducing these emissions is likely to be small.

On the other hand, livestock, and cattle in particular, contribute a much larger proportion of heat-trapping emissions globally than in the United States, so better pasture practices worldwide could have a substantial impact.

Practices that reduce the climate impact of pasture beef production would also curb other environmental effects, and are therefore highly worthwhile.

CHAPTER 3

Reducing Methane Emissions from Pasture Beef

Enteric fermentation accounts for more than 97 percent of methane emissions from beef cattle, while manure management accounts for about 2.5 percent (EPA 2010). Understanding how enteric fermentation and manure produce methane emissions can shed light on farm practices that can reduce those. This chapter provides an overview of methane emissions from beef cattle and possible mitigation practices on pasture and through feeding of harvested forage.

One effective approach to tackling enteric fermentation is to increase the efficiency with which cattle use feed, because more feed is then used to produce meat rather than methane. This approach entails ensuring that a unit of feed produces beef as quickly as possible, which reduces the amount of time when cattle emit methane.

The use of highly productive and nutritious forage species—perhaps reinforced by rotational grazing—can reduce methane emissions from enteric fermentation in pasture beef. Using feed additives and antibiotic-like substances (ionophors), and improving the genetics of beef cattle, could also help. However, this report does not consider ionophors because many pasture beef producers find them unacceptable. This report also does not consider the genetics of pasture cattle, although improving them could be an important way to boost productivity and thus reduce emissions, because information on that approach is limited.

How Ruminants Produce Methane

Ruminants—cattle, goats, and sheep—produce more methane than other livestock because of the unique physiology of their digestive systems. In the United States and globally, cattle are the most important source of methane emissions because they are more numerous and larger than other domestic ruminants. Methane emissions from sheep and goats in the United States are relatively minor.

The Rumen

Ruminants are named for the fore stomach, or rumen. The rumen is a large chamber containing many different types of microorganisms—bacteria, Archaea, protozoa, and fungi—that break down roughage. Roughage, especially cellulose and related substances, make up a large part of many types of plants such as grasses. The rumen allows ruminants to thrive on plants that other animals cannot use as effectively. The rumen empties into the other parts of the stomach and intestines, which do not produce as much methane, but where further digestion and absorption of nutrients takes place.

Methane-producing Archaea (single-celled microorganisms), or methanogens, use products from the metabolism of other microorganisms in the rumen to produce the energy and substances they need to grow. This process creates methane (Boadi et al. 2004). Some metabolic byproducts from rumen microorganisms contribute more than others to the ability of methanogens to produce methane. One strategy to reduce methane production is therefore to alter the proportion of metabolic byproducts to favor those that methanogens cannot use to produce methane.

The primary substances produced by rumen microbes that contribute to both the nutrition of cattle and methane production are called volatile fatty acids (VFAs), which cattle absorb directly (Boadi et al. 2004). There are three main types of these simple compounds. The biochemistry of one VFA—acetate—leads to the production of methane because its metabolism by microbes creates hydrogen gas (H_2), which methanogens then use to produce methane. Another VFA—proprionate—does not lead to the production of much hydrogen, and therefore not much methane. Practices, feed, and substances added to feed that favor the production of proprionate reduce methane emissions from cattle.

Here, a scientist with the U.S. Department of Agriculture's Appalachian Farming Systems Research Center records the species composition of a pasture. Such records are used by scientists and land managers to develop pasture management strategies that help farmers achieve production goals while meeting the nutritional needs of grazing livestock.

N. Wade Snyder, USDA-ARS

Although the rumen helps break down cellulose into smaller chemical units that cattle can use, the degradation of some substances in the rumen is less nutritionally efficient than when it occurs in the lower digestive tract. In particular, cattle can use protein more efficiently when digesting it in the intestines rather than the rumen (Min et al. 2003).

How Feed and Forage Affect Heat-Trapping Emissions

Practices that increase the efficiency with which feed or forage are converted into beef can decrease methane emissions per unit of meat. In fact, ruminants do not need the methane created in the rumen: it represents wasted food energy. Boosting feed efficiency also curbs other negative environmental effects such as nitrogen pollution from manure, because it allows cattle to grow faster, so they are on pasture for a shorter period of time.

Allowing cattle to feed on pastures with forage crops that are rapidly growing increases feed efficiency and decreases methane emissions, because these crops usually contain relatively more readily digestible components. When forage moves through the rumen quickly, digestion produces less methane, and usually more propionate than acetate (Boadi et al. 2004). Cattle also usually use a larger proportion of the forage for maintenance or growth, which means less is needed to produce a pound of beef. This reduces pollution by reducing the amount of manure per pound of beef.

Forage and feed with a high proportion of easily digested carbohydrates—such as starches and sugars—usually move through the rumen faster and are used more efficiently than forage and feed with a high proportion of roughage such as cellulose. Grain has a higher proportion of easily digested carbohydrates, especially starch, than forage, and is therefore used more efficiently.

However, as noted, a diet composed entirely of grain leads to diseases such as acidosis, which can cause death, because ruminants are not adapted to eating grain. That is why cattle in feedlot systems typically spend several months on pasture or nursing as calves, and eat grain only for the last four to eight months before slaughter.

Beef cattle eat forage plants such as grasses and legumes while on pasture. The feed efficiency of these plants varies substantially with the species, season, and growing method. However, improving the quality of this forage—that is, the proportion of easily digested carbohydrates—can reduce methane emissions substantially because that boosts feed efficiency.

Properties of High-Quality Forage

Pastures are often seen as synonymous with grass, and indeed many pastures consist only of it (except for weeds that may invade them). Many grasses make good forages for ruminants, and many are well-adapted to grazing. New growth arises from parts of the grass—called the meristem—near the soil surface, allowing grasses to regrow after normal grazing. Many grasses can also survive trampling by grazing ruminants.

Pasture legume species such as clover and alfalfa are usually higher-quality forage than grass species, because they often contain less cellulose and other structural components and more protein (Dewhurst et al. 2009; Waghorn and Clark 2004). Legumes also fix nitrogen; that is, they convert it from the air into a form that plants can use for growth.

The ability of legumes to fix nitrogen reduces the need to add nitrogen fertilizer to pastures that contain those plants. Because producing and applying synthetic fertilizers requires energy, legume pastures can also reduce farm energy inputs.

However, many legumes, including alfalfa, have several drawbacks. For example, they can cause bloat, a potentially fatal condition, if they compose too large a share of cattle diet (Howarth et al. 1991). Experts often recommend that legumes not exceed 30 percent of pasture for that reason, although some beef producers have used higher percentages.

Legumes may also have a higher-than-ideal protein-to-carbohydrate ratio. Cattle do not use protein as efficiently as non-structural carbohydrates such as starch to add weight. And because protein contains substantial amounts of nitrogen, excess protein—which ends up in manure—worsens nitrogen pollution, including nitrous oxide emissions. Finally, legumes often do not respond to heavy grazing as well as grasses.

For all these reasons, grazed pastures rarely consist only of legumes.[5] They typically also include grasses and sometimes other herbaceous plants such as chicory. Mixed-species pastures are often highly productive because the legumes supply the grasses with nitrogen, and the quality of the forage can be high (Sanderson 2010; Sleugh et al. 2000).

The season can also affect the quality, or efficiency, of pasture forage substantially. Many pasture plants, especially grasses, have higher proportions of lower-quality cellulose and lignin—another structural constituent—when they are mature. Forages are therefore much lower-quality later in the growing season (Waghorn and Clark 2004).

Measuring the Quality of Forage and Feed

Measuring feed quality and efficiency, and the resulting methane emissions, can shed light on farm practices that reduce those emissions. Studies of methane emissions from ruminants often target just one aspect of feed quality, which may be more or less useful in determining how much methane cattle actually produce on pasture.

What's more, analysts may measure methane emissions as a percentage of gross feed energy (GE or GEI), digestible feed energy (DM or GDE), or energy that can be metabolized (ME). These measures have different strengths and weaknesses, so directly comparing studies that use different measures is usually difficult.

For example, feed and forage that produce a low percentage of GE, DM, or ME as methane in laboratory research usually produce fewer methane emissions on the farm. However, GE measures the percentage of total caloric energy found in feed or forage used to produce methane. That measure says little about the amount of energy cattle can use efficiently.

Different measures sometimes also provide conflicting information on the value of various pasture practices in reducing methane emissions. For example, one study found that methane emissions from timothy hay would be 22 percent lower than those from alfalfa hay when measured as a percent of GE, but 27 percent higher when measured as a percent of DE (Benchaar, Pomar, and Chiquette 2001).

DM and ME consider the digestibility of forage. However, they do not distinguish between feeds that may be similarly digestible but nonetheless differ in quality (Waghorn and Clark 2004). For example, a hypothetical forage that is 70 percent digestible but largely protein will be lower in quality than a forage that is 70 percent digestible but has a substantial amount of sugars and adequate protein.

In practice, a unit of beef production—such as average daily weight gain, or ADG—is broadly useful in revealing the impact of a practice on methane emissions. This

5 Legumes, especially alfalfa in the United States, are often grown alone—that is, in monoculture—or in rotation with grains when harvested for hay or haylage.

In managed rotational grazing systems like this one, beef producers move cattle (seen on the right) among several small fenced paddocks. As the animals deplete the forage supply in one strip, they are moved to an adjacent strip. Such systems prevent overgrazing, encourage even distribution of manure, boost plant growth to optimal rates, and can improve the nutritional quality of pasture forage.

N. Wade Snyder, USDA-ARS

measure integrates aspects of forage quality tracked by more specific measures such as GE and DM. However, ADG does not always strictly measure forage efficiency, because it may not specify how much forage or feed cattle consume to gain a unit of weight. ADG may also fail to reveal the amount of land needed to produce beef, because measuring land use requires measuring the productivity, or yield, of forage or feed grain.

Because of its overall advantages compared with measures such as GE and DM, this report relies on ADG to evaluate the impact of a management practice on methane emissions when possible, and notes the particular measure of feed efficiency when available.

Practices That Reduce Methane Emissions from Enteric Fermentation

The Impact of Different Pasture Species

Most species of pasture grasses and legumes—the predominant pasture plants—are perennial. Perennials offer several advantages over annual crops grown for feed, such as corn, soybeans, and sorghum. For example, well-managed perennials provide groundcover throughout the year, reducing pollution runoff and soil erosion (Burkart et al. 2005).

Cattle that graze on pastures with some legumes usually have fewer methane emissions per unit of beef production than grasses. That is because grasses have more structural carbohydrates such as cellulose and lignin. In one study, models showed that hay from alfalfa, a legume, produced 21 percent fewer methane emissions than timothy hay, a grass (Benchaar, Pomar, and Chiquette 2001). Grass species may differ in their effect on methane emissions. However, these differences are usually narrower than those between grasses and legumes (Waghorn and Clark 2004).

Some legume species may improve pasture quality by competing better with grasses. The ADG of steers on pastures with mixed grass and kura clover (*Trifolium ambiguum*) in Wisconsin, for example, was 22 percent higher than that of steers on pastures with grass and red clover (another legume)—the latter a common mixture in the United States. The analysts attributed this difference to the fact that the percentage of kura clover was higher than that of red clover in the pastures (Mourino et al. 2003). Higher ADG, or growth rate, typically correlates with fewer methane emissions per unit of beef.

Legumes also typically produce more usable protein than grasses, although cattle that eat too much protein excrete more nitrogen, which may lead to more nitrous oxide emissions. As noted, legumes also supply companion grasses with nitrogen, boosting their growth and quality. For example, white clover added 99 to 231 kg of nitrogen per hectare to pasture mixtures (Ledgard, Penno, and Sprosen 1999). The amount depends on growing conditions, the share of legumes in the pasture mix, and other nitrogen inputs.

BOX 1. Reducing Emissions by Improving Pasture Crops: Birdsfoot Trefoil

Like other legumes, birdsfoot trefoil has desirable levels of protein, and also adds nitrogen to soil, improving the productivity of companion grasses and forbs (non-grass herbaceous species). However, unlike most cultivated pasture species, birdsfoot trefoil also produces condensed tannins (CTs).

CTs bind to proteins, and some forms, in moderate to large amounts, reduce feed efficiency by making proteins unavailable for digestion. However, the CTs in birdsfoot trefoil, at typical concentrations of 0.5 to 4 percent, improve feed efficiency by preventing protein from degrading in the rumen, and releasing it in the lower digestive tract where it is more efficiently absorbed (MacAdam et al. 2006).

In one study, birdsfoot trefoil reduced methane emissions by 32 percent per unit of product (milk solids) compared with good-quality ryegrass, with 66 percent of the reduction attributed to CTs (Woodward, Waghorn, and Laboyrie 2004). Moving protein digestion to the lower digestive tract also shifts some nitrogen in manure from urine to dung, which can reduce nitrous oxide emissions—which can be high in urine spots in pastures.

Yet managers of pasturelands have not widely adopted birdsfoot trefoil because its yield is often lower than that of alfalfa, it is less resistant to some soil-borne diseases, and it does not regrow after grazing as well as several other species. Establishing and reseeding birdsfoot trefoil is also often more difficult than with other species (MacAdam et al. 2006).

Plant breeders have tried to address several of these drawbacks. For example, they have created varieties of birdsfoot trefoil with a rhizomatous growth habit that is more grazing-resistant (Beuselinck et al. 2005). However, these varieties also have lower yields, and cattle may not graze them as efficiently. Agronomists have also developed techniques for establishing this legume more easily (MacAdam et al. 2006).

Recent research suggests that land managers could reduce the climate change impact of pasture forage significantly by planting birdsfoot trefoil (Beuselinck et al. 2005). Still, plant breeders could do much more to improve the yield of birdsfoot trefoil and the range of conditions under which it can be productive—especially by developing varieties that resist root and crown diseases prevalent in the eastern United States.

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Nitrogen from legumes also increases the amount of biomass in a pasture, so beef producers may need less land. Because producers often add synthetic nitrogen to bolster the productivity and quality of pasture with only grass, planting legumes also lowers fertilizer costs.

However, several important pasture legume species, including alfalfa and clovers, may cause bloat when they account for as little as 15 percent of cattle diet (Howarth et al. 1991). Some legumes that produce phenolic substances called condensed tannins (CTs) do not produce bloat, and cattle may eat them at much higher rates (see Box 1). Adding CTs to forage can reduce or eliminate bloat (Min et al. 2006), and some plant breeders are trying to develop alfalfa that does not cause bloat.

CTs may also reduce the amount of methane produced during enteric fermentation. Daily methane emissions from goats fed sericea lespedeza (*Lespedeza cuneata*)—a legume that contains CT—dropped by 30 percent, and by 57 percent as a fraction of dry matter intake (Puchala et al. 2010).[6] And methane emissions rose when researchers removed CT from birdsfoot trefoil, a forage (Woodward, Waghorn, and Laboyrie 2004).

Legumes tend to be less resilient in the face of trampling by cattle, and grass species often outcompete legumes over several years, reducing their percentage in the pasture. Good management is therefore critical to maintaining legumes in pastures.

Different legumes also grow best in different types of soil and climates. For example, alfalfa grows best in neutral, well-drained soil, while birdsfoot trefoil can tolerate more flooding (MacAdam et al. 2006). Many legumes do not grow well in acid soils, which are common in warmer climates such as the southeastern United States, as those soils often have limited amounts of important plant nutrients and may also contain toxic levels of aluminum. (Graham and Vance 2003). However, plant breeders may develop species of pasture legumes that—along with their symbiotic, nitrogen-fixing rhizobial bacteria—tolerate acid soils and other challenging conditions (Howieson, O'Hara, and Carr 2000).

Pasture Maturity, Nitrogen Fertilizer, and Productivity

Forage crops become less digestible and decline in quality during the growing season and growth cycle, because they produce more structural components such as cellulose and lignin. That, in turn, slows animal growth and increases methane emissions per unit of forage consumed or beef produced.

One study showed that methane emissions from cattle feeding on fast-growing grass were 25 percent lower than from cattle feeding on mature grass, based on gross energy intake (Robertson and Waghorn 2002). Another study found no difference in methane emissions from heifers eating highly digestible (fertilized, low stem-to-leaf ratio) perennial ryegrass and those eating less-digestible ryegrass (slower-growing, with a higher stem-to-leaf ratio typical of maturity), based on dry matter intake (Hart et al. 2009). However, the low-quality ryegrass produced higher methane emissions based on weight gain (ADG). The authors concluded that the use of higher-quality forage could reduce methane emissions per unit of animal product. A third study, based on modeling, showed a 15 percent reduction in methane emissions from young versus mid-bloom alfalfa, based on digestible energy (Benchaar, Pomar, and Chiquette 2001).

Legumes are desirable in pasture not only because of their high feed quality but also because they lose less quality as they mature. In one study, the amount of energy in ryegrass that cattle could metabolize dropped 25 percent as it matured, while the energy in mature white clover fell only 9 percent (Waghorn and Clark 2004).

Pastures with complex mixtures of species, known as polycultures, may be more productive than those with fewer species. Typical mixtures consist of a grass and a legume species, with some percentage of weeds. However, mixtures of up to nine species of grasses, legumes, and non-legume forbs produced higher turf yields in dryer years in the eastern United States (Sanderson 2010; Deak, Hall, and Sanderson 2007; Sanderson et al. 2005).

The higher productivity of pasture mixtures appears to be driven largely by the specific combination of legumes and grasses, and the single best-yielding species, rather than by polyculture per se. However, polycultures may have other advantages, such as better weed suppression (Picasso et al. 2008).

Using Harvested Forages: Silage and Pelleting

Harvested forages—silage and hay—are an important component of pasture beef farms in many parts of the

6 Sericea lespedeza is, however, less nutritious than other legumes.

country. Cattle may eat harvested forages when pastures are dormant or have matured, and are growing slowly or not at all. In fact, cattle fed on these forages can produce fewer heat-trapping emissions than cattle grazed on dormant pasture because the latter are less nutritious, and less able to absorb nitrogen from manure.

Reducing the particle size of forages—such as by grinding rather than chopping them—can reduce methane emissions 20 to 40 percent by making the feed more digestible (Johnson et al. 1996). And pelleting rather than chopping alfafa hay could reduce methane emissions by 13 percent, according to models (Benchaar, Pomar, and Chiquette 2001). A diet composed largely of pelleted alfalfa could lead to acidosis, but beef producers might improve feed quality by combining pelleted alfalfa with other forages.

Preserving forage as silage—a fermented form—is a common practice. The use of alfalfa silage rather than alfalfa hay reduced methane emissions by 28 percent, based on digestible energy, modeling showed (Benchaar, Pomar, and Chiquette 2001).

Together these studies suggest that cattle can maintain a high-quality forage-based diet even when they are not on pasture.

Using Breeding to Improve Pasture Productivity and Reduce Emissions

Improving the productivity of pastures through plant breeding could reduce methane emissions. The yield of alfalfa—the most widely grown U.S. pasture and forage crop—has risen by only about 20 percent since 1970, despite receiving more breeding effort than other pasture species (USDA NASS n.d.). If about half of that increase stems from breeding, then breeders have bolstered alfalfa yields by only about 10 percent over the past 40 years—

TABLE 1. Methane Reduction from Improved Pasture Practices

Methane Reduction Practice	Standard Practice	Methane Reduction (%)	Measurement Basis for Reduction	Reference
Birdsfoot trefoil	High-quality ryegrass	32	Reduction per unit of milk	Woodward, Waghorn and Laboyrie, 2004
Rapidly growing perennial grass	Mature perennial grass	25	Gross energy intake units	Robertson and Waghorn, 2002
High-quality ryegrass	Low-quality ryegrass	0* Unspecified decrease	Dry matter intake units Average daily gain (ADG)	Hart et al. 2009
Young alfalfa	Mid-bloom alfalfa	15	Digestible energy units (modeling)	Benchar, Pomar, and Chiquette 2001
MRG, perennial pasture grasses, nitrogen fertilizer, overseeded with annual ryegrass	Untreated perennial pasture grasses	22	ADG (?)	DeRamus et al. 2003
Alfalfa silage	Alfalfa hay	28	Digestible energy units (modeling)	Benchar, Pomar, and Chiquette 2001
Pelleted (ground) forage	Chopped forage	20–40	ADG (?)	Johnson et al. 1996
Pelleted (ground) alfalfa hay	Chopped alfalfa hay	13	Digestible energy units (modeling)	Benchar, Pomar, and Chiquette 2001

* The authors note that if measured as methane produced per unit of beef, the high-quality forage is expected to result in less methane production.

far less than they have improved the yields of corn and soybeans used for cattle feed.[7]

Public-sector resources devoted to alfalfa breeding, measured as scientist-years, actually fell by 46 percent from 1994 to 2001 (Traxler et al. 2005, Table 11). Today few public-sector breeders—such as those at the Agricultural Research Service of the U.S. Department of Agriculture and state agriculture experiment stations—work on forage crops (Frey 1996, Table 9). Yet gains in yields of more than 1 percent per year are feasible, and newer selection methods may result in even higher gains (Casler and Brummer 2008).

Analysts have noted the significant untapped potential for breeding to improve forage grasses, such as by increasing the share of non-structural, readily digestible carbohydrates in forage species (Wilkins and Humphreys 2003). Researchers have made some progress in boosting the sugar content of ryegrass. Beef cattle on high-water-soluble carbohydrate ryegrass gained an average of 1.11 kg per day over two years, while cattle on control ryegrass gained 0.89 kg per day—a 25 percent difference (Marley et al. 2005).

Extending the active growth period and shortening the dormant period of forage species would also improve feed quality. Boosting the amount of growth per unit of nitrogen added to a pasture could reduce nitrous oxide emissions and overall nitrogen pollution (Bregard, Belanger, and Michaud 2000). And extending the geographic range of desirable forage species could enable beef producers to expand the acreage of high-productivity pasture.

Finally, as noted, enabling legumes to better compete with grass could help sustain a higher percentage of legumes in perennial pastures. However, renovating perennial pastures requires more resources than growing annual crops, so farmers may need incentives to plant new pasture perennials.

Better Pasture Management: Rotational Grazing

Managed rotational grazing (MRG)—also known as managed intensive rotational grazing—boosts the productivity of pasture, and can improve the nutritional quality of pasture forages. In MRG, beef producers rotate grazing cattle often among several fenced paddocks within a pasture. MRG prevents cattle from overgrazing, which curbs the ability of pasture plants to grow, and allows paddocks to recover between grazing periods. MRG also promotes more uniform grazing, so pasture plants can grow at optimal rates. Under continuous grazing, in contrast, cattle graze anywhere on a pasture at will.

However, the data on the effect of MRG on methane emissions are ambiguous, and insufficient to draw clear conclusions about the impact on climate change. According to one study, methane emissions were 22 percent lower on southern pastures that used MRG than on those using continuous grazing. However, the MRG paddocks were also overseeded with annual rye and fertilized three times, which likely improved pasture quality (DeRamus et al. 2003). Studies in Canada found no difference between MRG and continuous grazing at two stocking densities (the number of cattle per unit of land), measured as methane emissions per ADG (McCaughey, Wittenberg, and Corrigan 1997).

Managed rotational grazing has become more feasible and less costly owing to the advent of portable electric wire fencing. These fences can be powered by batteries, and readily moved to enclose new paddocks because they are relatively lightweight and flexible.

Summary: The Potential for Reducing Methane Emissions from Pasture Beef

These improved practices—available now—could reduce methane emissions from pasture beef considerably. Exactly how much depends on the farm practices they would replace. Beef producers using continuously grazed pastures with a single grass species and low productivity could reduce methane emissions by at least 15 to 30 percent. They could do so by adopting just one or two best practices, such as diversifying pasture species and planting legumes, and may achieve greater reductions by adopting several other practices, such as feeding high-quality forages instead of grazing on low-quality mature pasture.

Table 1 summarizes methane reductions for various improved practices. However, their reported efficacy is based on a limited number of studies. Whole-farm studies are needed to shed more light on the impact of these practices on methane emissions, the extent to which land managers now use them, and the barriers to wider use. Researchers also need to investigate climate change tradeoffs among different management practices. Until that information is available, accurately predicting cuts in methane emissions from specific practices is not feasible.

7 This analysis is based on five-year averages calculated from U.S. Department of Agriculture data.

CHAPTER 4

Reducing Nitrous Oxide Emissions from Pasture Beef

The average estimate of U.S. agricultural emissions of nitrous oxide grew 7 percent from 1990 to 2008 (EPA 2010). Land managers can make significant cuts in those emissions from pasture-raised beef—in some cases with better economic performance.

Some 92 percent of nitrous oxide emissions from U.S. agriculture come from soils used to grow row crops such as corn and wheat, and range and pasture grasslands (EPA 2010). Both direct and indirect sources—including nitrogen from soil leached into groundwater—produce these emissions.

Estimates of nitrous oxide emissions from U.S. agriculture range from 154 MMT of CO_2 equivalent to 389 MMT of CO_2 equivalent (EPA 2010).

Crop soils produce an average of about 153 MMT of CO_2 equivalent of nitrous oxide, while grasslands—including manure deposited directly onto them—produce about 62 MMT. A large share of grasslands is devoted to cattle production, especially cow-calf operations. A substantial fraction of cropland, meanwhile, is used to produce grain-based feed—much bought by beef CAFOs.

Managed manure—stored manure, as opposed to manure applied to fields—from U.S. beef cattle produces 7.4 MMT of CO_2 equivalent of nitrous oxide emissions per year, largely from CAFOs. That means beef manure management accounts for 43 percent of nitrous oxide emissions from overall livestock manure management, and 3 to 4 percent of nitrous oxide emissions from U.S. agriculture (EPA 2010).

Key Factors in Nitrous Oxide Emissions

Nitrogen enters the farm environment from three main sources: synthetic fertilizer, manure from livestock, and biological nitrogen fixation. The latter occurs when bacteria associated with the roots of some plant species convert, or "fix," nitrogen gas, N_2, from the atmosphere into ammonia. Legume crops such as soybeans and alfalfa are the most important plants that fix nitrogen.

The movement of nitrogen through the environment—often over long distances—and its conversion into different chemical forms is called the nitrogen cycle. Understanding how harmless forms of nitrogen, such as nitrogen gas, convert into harmful forms such as nitrous oxide can allow beef producers to exert more control over the cycle.

The nitrogen cycle is complex because linked soil microbial processes—nitrification and denitrification—convert ammonia, nitrate, nitrous oxide, and other important forms of nitrogen into one another, with the amounts determined by interactions among soil, microbes, plants, animals (including livestock), and climate.

The nitrogen cycle is also intimately connected to the carbon cycle, because carbon fuels the metabolism of the microorganisms in soil and plants that convert nitrogen into different forms. The complexity of the nitrogen cycle—and its dependence on factors that change over time and under different conditions—makes it challenging to accurately predict the amounts of different forms of nitrogen a farm produces.

The complexity of the nitrogen cycle also means that a number of farm practices and technologies can affect the cycle—including nitrous oxide emissions. That means no single set of practices will likely prove superior in reducing nitrous oxide emissions in all circumstances.

Nitrate (NO_3) from agricultural sources—another chemical in the nitrogen cycle—is a primary cause of water pollution, including dead zones in coastal waters and estuaries. A third chemical in the cycle, ammonia (NH_3), pollutes the air when volatilized, and acidifies soil when precipitating back to earth, reducing biodiversity (Gurian-Sherman 2008).

Ammonia is a common form of nitrogen found in livestock manure and some synthetic fertilizers. Ammonia

Kim Cassida, USDA-ARS

Over-seeding legumes into grass pastures improves overall forage quality with the added benefit of the legume plants fixing atmospheric nitrogen into the soil for use by other pasture plants. Here, a USDA scientist is hand-seeding red clover into research paddocks at the Appalachian Farming Systems Research Center.

often easily converts to nitrate in soil. Nitrate, also a component of many synthetic fertilizers, leaches into groundwater more readily than ammonia. Fossil fuel combustion and industrial processes are the primary sources of nitric oxides (NOx, as opposed to nitrous oxide, or N_2O), which, along with ammonia, are an important cause of air pollution, and water pollution after they precipitate.

Many scientists consider nitrogen pollution among the most important causes of global environmental degradation (Rockström et al. 2009). Because the farm environment includes substantial amounts of nitrous oxide, ammonia, and nitrate, beef producers should consider all three when evaluating their management practices.

Nitrogen pollution is often associated with pollution from phosphorus, another major plant nutrient. Both manure and fertilizers are sources of phosphorus as well as nitrogen, so beef producers should also consider phosphorus pollution (not addressed here) when evaluating their management practices.

Despite their negative environmental effects, nitrate and ammonia are critical plant nutrients, and farmers often add large amounts of nitrogen fertilizer to soil to promote crop growth. Farmers and managers of pasturelands may also provide nitrogen by spreading livestock manure or cultivating legumes.

Nitrogen—a major component of proteins and nucleic acids (DNA and RNA)—is also an essential animal nutrient. Cattle acquire it by eating plants. Livestock and plants do not require nitrous oxide—a by-product of microbial metabolism of nitrate and ammonia in soil—so reducing nitrous oxide emissions does not curb the productivity of crops or livestock directly. However, cutting the nitrogen supplied to feed crops and pastures to reduce nitrous oxide emissions may reduce their productivity—and hence that of beef cattle.

The three main forms of nitrogen important to agriculture—as opposed to the organic forms in plants and animals—cause harm primarily when large amounts escape the farm environment. Beef producers can curb nitrogen pollution by keeping the nitrogen cycle as tight as possible, limiting leakage among crops, soil, and livestock. Practices for reducing nitrous oxide emissions focus on reducing both the use of nitrogen and its loss from the farm or conversion into nitrous oxide.

Leading Causes of Nitrogen Pollution from Pasture Beef

Nitrous oxide emissions and other types of nitrogen pollution usually rise with increasing nitrogen use on a farm. Limiting the use of nitrogen fertilizer and manure on pasture crops to the amount needed therefore usually reduces those emissions, as well as other types of nitrogen pollution.

On the other hand, nitrogen fertilizer usually increases the quality and amount of pasture grasses by boosting their growth rate and the proportion that is readily digestible. That, in turn, reduces the amount of methane cattle emit and nitrogen they excrete per unit of meat production. Land managers must therefore make trade-offs between the productivity of pasture grasses and beef production on the one hand and nitrogen pollution on the other.

Manure

Manure is a valuable source of plant nutrients such as nitrogen and phosphorus as well as organic matter. Applying manure to pastures recycles much of the nitrogen and other nutrients that cattle have removed through grazing or consuming harvested forage. Returning manure to the pasture therefore partially closes the nitrogen cycle. The two components of manure—dung and urine—both contain nitrogen, and both therefore fertilize crops. However, they also lead to the emission of nitrous oxide.

Manure produced by grazing cattle is an important source of nitrous oxide emissions and leached nitrate. Cattle tend to spend more time in some parts of a pasture—such as near water and shade or other shelter—where they deposit more manure. Manure patches are particularly conducive to nitrous oxide emissions because nitrogen levels may be higher than crops need.

Dung usually produces fewer nitrous oxide emissions than urine because only 20 to 25 percent is in water-soluble, rapidly convertible forms, while the rest is in organic forms. Some 50 to 80 percent of urine, in contrast, is urea, which can quickly convert to ammonia. Practices that shift nitrogen in urine to nitrogen in dung can therefore reduce nitrous oxide emissions (Haynes and Williams 1993; Kirchmann and Witter 1992).

Cattle may compact the soil in heavily used areas, reducing the flow of water and the pore spaces in soil, which allow air to permeate. Higher water content and lower oxygen content often lead to higher nitrous oxide emissions (Saggar et al. 2004b). The amount of compaction reflects the size and number of cattle and how long they spend in a particular area, the type of soil, and the type and quality of pasture crops.

Legumes

As noted, land managers often grow legumes with grasses to supply them with nitrogen (Ledgard 1991). Soil microbes can convert this organic nitrogen to nitrous oxide emissions and other forms of nitrogen pollution. The contribution of legumes to heat-trapping emissions and other forms of nitrogen pollution must therefore be considered.

Other Contributors to Nitrous Oxide Emissions

The nitrifying and denitrifying bacteria in soil that produce nitrous oxides from other nitrogen compounds need moisture to grow. Some studies suggest that nitrous oxide emissions rise when the amount of pore space between soil particles that is filled with water exceeds about 60 percent (Linn and Doran 1984). Nitrous oxide emissions also rise with higher soil pH, temperatures, and amounts of soluble carbon (Frolking et al. 1998).

Because the factors underlying nitrous oxide emissions interact in complex ways, depending on environmental conditions, those emissions can vary considerably among individual farms and even fields. That, in turn, means that beef producers need to carefully consider best practices for reducing those emissions.

Curbing Nitrous Oxide Emissions from Pasture Beef

Using Less Fertilizer and Using It Better

Land managers can limit nitrous oxide emissions while maximizing the productivity of pasture grasses by applying the amount of nitrogen fertilizer the grasses actually need. Some nitrogen fertilizer will be lost as nitrous oxides even if land managers apply small amounts of fertilizer, because the microbes that produce those emissions compete with plant roots for nitrogen. However, the more the amount of nitrogen applied to a field exceeds the ability of plants to use it, the more that is converted to nitrous oxides.

A unit of nitrogen also spurs more plant growth when little nitrogen is already available (Cassman et al. 2003). Adding more than 100 to 150 kg of nitrogen per hectare therefore produces little additional yield of corn, for example (Figure 2). Much of the extra nitrogen becomes nitrous oxide or nitrate, which escapes into groundwater. However, the amount of unused nitrogen varies by pasture or grain crop, temperature, moisture, and other plant nutrients in soil.

Because plants absorb nitrogen over time, applying too much at once can produce substantial nitrous oxide emissions. Land managers can tackle that problem partly by applying smaller amounts of nitrogen more often (Cassman et al. 2003). They can also better match the nitrogen supply to crop needs by using fertilizers that release nitrogen more slowly than ammonia or urea fertilizers (Hyatt et al. 2010).

Cool-season grasses such as perennial ryegrass (*Lolium perenne*) and tall fescue (*Festuca arundinacea*) grow more quickly in spring than in summer. Nitrogen applied when grass is growing slowly is more likely to be lost during rain or snow, and to subsurface water flow (Owens, Edwards, and Van Keurcn 1994; Stout and Jung 1992).

Land managers can reduce nitrous oxide emissions and nitrate leaching by boosting pasture growth rates during otherwise dormant seasons. Seeding winter rye (*Secale cereale*) into orchardgrass, for example, reduced the amount of time a pasture was dormant and cut nitrous oxide emissions as much as threefold (Sauer et al. 2009).

Land managers can also reduce nitrous oxide emissions and nitrogen leaching by applying nitrogen during dry weather and when soil moisture is low (Saggar et al. 2004a). However, a substantial portion of urea fertilizer may be volatilized under dry conditions as ammonia, causing other environmental harm.

In sum, applying appropriate amounts of nitrogen at the right time, such as when pasture species are actively growing, may reduce both nitrous oxide emissions and other nitrogen pollution without sacrificing much crop and beef productivity.

Reducing Emissions from the Manure of Grazing Cattle

Beef producers can use several techniques to ensure the even distribution of nitrogen in manure on grazed pastures. Reducing the amount of time cattle are on pasture is perhaps the most obvious approach. However, keeping cattle in confinement facilities for longer periods of time leads to challenges for distribution of large amounts of stored manure onto crops or pastures while limiting nitrous oxide or other pollution.

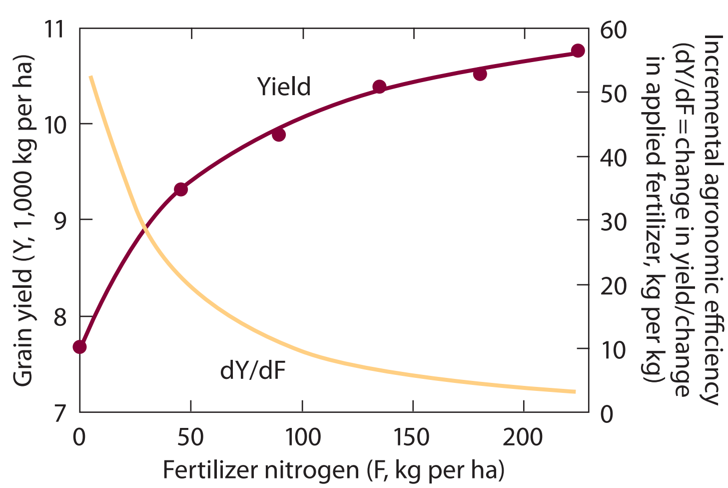
Farmers can also keep cattle off pasture that is not rapidly growing to limit the amount of nitrogen from manure, and reduce the amount converted to nitrous oxide, leached into groundwater, and volatilized as ammonia. Keeping cattle on pasture in winter can lead to high nitrogen loss, especially if ground is frozen, because the manure collects and soil microbes do not metabolize it as quickly. That can lead to especially large releases of nitrogen and nitrous oxides when temperatures warm in the spring.

Farmers can also improve the distribution of manure on grazed pasture by reducing the size of paddocks and shifting animals to new ones more often, or moving shelter or water sources so cattle congregate in different parts of the pasture. They can also reduce stocking numbers—the number of cattle per unit of land. Low stocking numbers may reduce the productivity of beef production, but moderate stocking densities can provide high productivity without dramatic increases in nitrous oxide emissions.

Beef cattle typically use only a small percentage of dietary nitrogen for growth, so optimizing their intake reduces its concentration in manure. Higher-quality forage also shifts some nitrogen from urine to dung. Pasture containing ryegrass with high-water-soluble carbohydrate reduced nitrogen content in the urine of dairy cows by 26 to 28 percent, for example (Moorby et al. 2006; Miller et al. 2001). Forage containing condensed tannins, such as birdsfoot trefoil, may reduce nitrogen loss from urine by reducing protein degradation in the rumen and allowing more digestion in the intestines (Waghorn et al. 1998).

Dairy farmers on sandy soils in the Netherlands reduced nitrogen and phosphorus losses by integrating crop and livestock production, using both pasture and harvested annual forage crops for feed and adopting several other best management practices. For example, the farmers

FIGURE 2. Grain Yield and Applied Nitrogen on Irrigated Cornfields in Eastern Nebraska



Source: Cassman et al. 2003.

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reduced the amount of time cattle spent on pasture to four or eight hours per day, and then collected manure from shelters to distribute more uniformly on crops. The farmers also reduced their use of chemical fertilizer and corn silage, to curb excess nitrogen in the cows' diet. Milk production per cow rose while excess nitrogen dropped by 32 percent (Rotz et al. 2005).

Boosting the Efficiency of Nitrogen Use by Improving Pasture Crops

As noted, beef producers can reduce the amount of nitrogen lost to nitrous oxide emissions, leaching, and volatilization by adding less fertilizer and manure to pastures, and by optimizing the nitrogen intake of cattle. Pasture crops also differ in the amount and efficiency with which they remove nitrogen from the soil, and pasture crops can be bred to be more efficient in their use of nitrogen. These approaches are called improving nitrogen use efficiency (NUE). NUE can be measured as the amount of product—such as the yield of pasture plants—that results from a given amount of added nitrogen. Ensuring that beef cattle use nitrogen in feed more efficiently is NUE of the cattle rather than the crop.

The few studies that have compared the NUE of pasture grass species show differences in NUE. These differences may be exploited to reduce nitrogen loss and nitrous oxide production, and also show that more work is needed to better understand NUE in pasture crops. At two sites in Wisconsin, orchardgrass (*Dactylis glomerata*) had higher NUE over a range of nitrogen input levels, under drought conditions, and for a greater part of the growing season than either smooth bromegrass (*Bromus inermis*) or Kentucky bluegrass (*Poa pratensis*). For example, mean apparent nitrogen recovery for the different nitrogen application rates at the two test sites ranged from 0.17 to 0.44 kg nitrogen recovered (per kg N applied) for smooth bromegrass, and 0.32 to 0.50 kg nitrogen recovered for orchardgrass (Zemenchik and Albrecht 2002). In Iowa, orchardgrass removed more nitrogen from soil than smooth bromegrass (Singer and Moore 2003).

One reason orchardgrass had higher NUE is that its period of active growth is longer than that of the other grasses. Pastures lose more nitrogen when they grow more slowly, such as when cool-season grasses in temperate climates become dormant in summer.

Unlike cash crops, pasture crops often grow in mixtures, and land managers can tap the genetic and phenotypic potential of several species. Few researchers have investigated which combinations of pasture crops could boost NUE. However, they have found that some species—especially forbs—often produce deeper root systems than grasses, and may be better able to capture nitrogen lower in the soil profile. Deeper root systems reduce not only nitrate leaching but also the considerable nitrous oxide emissions that result from it. Deeper root systems may also facilitate growth under drought conditions.

Deeper-rooted pasture species may also add more carbon to pasture soils, although that potential remains largely unexplored.

Growing mixtures of pasture species with complementary root-growth habits could optimize root density throughout the soil profile. Research in Brazil shows that it is possible to improve rooting depth in pastures, and the rooting potential of pasture species deserves more exploration (Gewin 2010; Fisher et al. 1994).

However, land managers need to consider possible tradeoffs between improved NUE and other important qualities of forage crops. For example, if a pasture species provides higher NUE but lower feed quality, slower cattle growth and higher methane emissions may offset more efficient nitrogen use. These complexities mean that plant breeders need to bolster the multiple qualities important to pasture crops.

Breeders have made some progress in improving the NUE and other qualities of forage crops. However, they have devoted substantially less effort to developing better forage crops than to improving cash crops (Wilkins and Humphreys 2003). That difference partly reflects the lower value of seed for forage crops compared with seed for cash crops such as corn and soybeans. However, the untapped potential to boost the NUE of forage crops is considerable (Casler and Brummer 2008). Public-sector plant breeding programs need to maximize that potential while extension services and incentive programs need to encourage the private sector to adopt new varieties of pasture plants.

Inhibiting the Production of Nitrous Oxides and Ammonia

Scientists have tested several compounds for their ability to reduce nitrous oxide emissions from urine deposited onto pastures. Urease inhibitors prevent the conversion of urea—the major form of nitrogen in urine—to ammonia, which can then be converted into nitrous oxide. Several other compounds inhibit the nitrification process, which also ultimately leads to nitrous oxide emissions.

The nitrification inhibitor dicyandiamide (DCD) is perhaps the most widely used compound, reportedly applied to 3.5 percent of dairy pasture in New Zealand, for example. One 50-day field experiment found that DCD cut nitrous oxide emissions by about 50 percent (Giltrap et al. 2010).

The fate of ammonia in urine while DCD is present and after it decays is unclear, and depends partly on how much of the compound pasture crops can use. Because nitrogen concentrations in cattle urine are high—sometimes topping 1,000 kg per hectare—even actively growing pasture grasses may absorb only a fraction (Wachendorf, Taube, and Wachendorf 2005). Ammonia remaining in the soil after DCD breaks down could be converted to nitrous oxide.

Lab researchers have found that temperature and different soil types affect the rate at which DCD decays, which influences how long DCD can remain effective after application (Singh et al. 2008). And research on the impact of DCD on soil biology and other aspects of the environment has been limited.

Summary: Nitrogen Use and Nitrous Oxide Emissions from Pasture Beef Production

Several practices can or could reduce the use and deposition of nitrogen in pastures—which in turn should curb nitrous oxide emissions. However, field measurements of the impact of these practices on farms are often lacking. Practices that reduce nitrate leaching into groundwater may also reduce nitrous oxide emissions, but researchers similarly need to measure that outcome.

CHAPTER 5

Using Pastures to Sequester Carbon Dioxide from the Atmosphere

Well-managed pasture soils sequester carbon. Although agriculture in the United States does not produce as much carbon dioxide as methane and nitrous oxide, using soil to sequester carbon can reduce the climate change impact of beef production. This chapter evaluates the factors that influence carbon sequestration rates in pasture.

Sequestration begins with photosynthesis, whereby plants convert carbon dioxide into carbon-containing compounds such as sugars, and then to more complex molecules such as cellulose and lignin. Some of these carbon-containing components eventually return to the soil in the form of plant roots, root exudates, plant residues, and manure produced by animals that eat those plants.

Soil microbes that consume plant biomass convert much of it back to carbon dioxide. The remaining material contributes to microbial biomass, while some is bound to mineral particles or remains as particulate organic matter.

Soil cannot sequester an unlimited amount of organic carbon. Eventually the amount lost through microbial activity—even under conditions favorable to sequestration—offsets the amount that accumulates. However, high rates of carbon sequestration may continue for 40 years or more (Conant, Paustian, and Elliott 2001).

Sequestering organic carbon in soil provides other important benefits beyond mitigating climate change. Organic carbon aerates soil; boosts root growth, water flow, and water retention; and purifies water before it flows into groundwater.

U.S. pasture and rangeland soils have the capacity to sequester 13 to 70 MMT of carbon per year, including 10 to 34 MMT in pasture alone (Lal et al. 2007). Together crop and grazing lands could sequester about 15 percent of global warming emissions from U.S. agriculture each year.

Perennial pasture species are particularly effective at sequestering carbon because their substantial root systems grow in spring, in contrast to annual crops such as corn, which are just beginning to grow at that point. Pastures in the U.S. Southeast sequestered 0.30 to 0.84 metric ton, or megagram (Mg), of carbon per hectare per year, according to two studies (Franzluebbers 2010; Schnabel et al. 2001). Another study found that if land managers improve several practices, pastures can sequester 0.8 Mg of carbon per hectare per year (Ogle, Conant, and Paustian 2004).

Practices That Affect Carbon Sequestration

Many farm practices—along with climate and soil conditions—influence the rate of carbon sequestration in pastures. New practices can greatly enhance that rate. For example, adding irrigation can enable pastures to sequester an additional 0.1 Mg of carbon per hectare per year, while growing improved grass species can add 3.0 Mg of carbon per hectare per year (Conant, Paustian, and Elliott 2001).[8]

Practices that increase the productivity of pastures—and thus the amount of biomass added to soil—tend to boost carbon sequestration. These practices include spreading manure or synthetic fertilizers containing nitrogen, phosphorus, and possibly other minerals on pastures deficient in plant nutrients, and adding legume species to grass pastures.

8 Several practices with the highest sequestration rates were based on a limited number of studies, and may include some special cases.

Here, USDA scientists evaluate a managed intensive grazing system for cattle. The area on the right has been grazed for three weeks, while the area on the left has rested and is ready for grazing by cattle.

Jeff Vanuga, USDA-NRCS

Because adding too much nitrogen fertilizer increases nitrous oxide emissions and the amount of nitrate leaching into groundwater, that practice can offset any increase in carbon sequestration (Conant, Paustian, and Elliott 2001; Lee and Dodson 1996). The manufacture of synthetic fertilizer also uses energy, and therefore produces heat-trapping emissions. Land managers therefore need to carefully calibrate their use of nitrogen fertilizer to the needs of specific pastures.

Pastures that see low to moderate amounts of grazing may actually sequester more carbon than ungrazed pastures. For example, pastures in the southeastern United States with low grazing pressure had about 25 percent more carbon than ungrazed pastures (Franzluebbers and Stuedemann 2009). Harvesting pastures for hay or silage may reduce carbon sequestration if land managers do not cycle the carbon back to the pastures in the form of manure.[9]

Climate influences the rate of carbon sequestration directly because it affects the productivity of pasture plants. Low precipitation and short growing seasons reduce the productivity of pastures, for example. Climate also affects carbon sequestration indirectly by altering the rate at which soil microbes metabolize carbon. Adequate precipitation and higher temperatures, for example, boost the respiration rates of soil microbes—which in turn increases the rate at which they turn over soil carbon.

High cattle stocking densities reduce both carbon inputs and available forage, so the amount of carbon in soil and animal productivity both decline (Follett and Reed 2010, Table 3). Appropriate stocking densities—and therefore beef production per unit of land area—vary with the productivity of the land. That, in turn, depends on climate, soil type, pasture species, and management practices.

Limited evidence shows that managed rotational grazing can increase carbon sequestration on pasturelands.

9 A full accounting should also consider where this manure is ultimately deposited, and how much carbon is lost through respiration of microbes, including methane emissions from enteric fermentation. Carbon is also removed from pasture in the form of beef and other cattle products, and as carbon dioxide released through respiration.

MRG increased soil carbon by 0.41 Mg per hectare per year at four sites in the U.S. Southeast, compared with similar sites with continuous grazing (Conant, Six, and Paustian 2003). These researchers noted that MRG is not widely practiced despite evidence that it is more cost-effective than extensive grazing. Indeed, U.S. pasture and rangelands receive little management (Lal et al. 2007).

How Much Carbon Can Pastures Sequester?

As noted, carbon can accumulate in pasture soil for several decades. How much actually does accumulate depends on how much carbon the land lost owing to previous farming or other practices (Follett and Reed 2010). Poorly managed soil looses carbon relatively quickly, so land managers must sustain favorable practices indefinitely to prevent the reversal of sequestration gains.

Replacing grain crops now grown on marginal lands with pasture could allow those lands to sequester considerable amounts of carbon. Conversely, converting grasslands and forests to fields that grow annual crops—such as corn used for ethanol or beef feed—can lead soil to lose carbon (Searchinger et al. 2008). The latter is occurring: the amount of U.S. land devoted to corn rose from an average of 78.3 million acres from 2000 to 2003 to an average of 88.5 million acres from 2007 to 2010—a 13 percent increase (USDA NASS 2010). Because of such shifts, U.S. agricultural lands had lost 2,500 MMT of carbon by 1990 (Houghton, Hackler, and Lawrence 1999).

Much of the converted land may be moderately rather than highly productive (see Chapter 6). Converting croplands back to pasturelands could therefore allow them to sequester significant amounts of carbon. However, because much land used to grow annual crops produces feed for livestock in CAFOs, it is important to compare the climate impacts of CAFOs with those of pasture, to determine the wisdom of making such a shift. The next chapter considers that comparison.

Overall, U.S. pasturelands have considerable potential to sequester carbon. However, until we know more about the plant species they now host, the practices pasture managers now use, and the amount of carbon pasture soils now contain, analysts can only roughly estimate how much carbon better management practices could enable soil to sequester.

Jackson Grassland Ecology Lab, University of Wisconsin–Madison

Soil core samples like this one can be used to determine the amount of carbon captured and stored in the soil by pasture plants.

CHAPTER 6

The Climate Impact of Pasture Finishing versus CAFOs

Feedlots, or CAFOs, are the predominant means of finishing beef in the United States. Comparing the climate impact of CAFOs with that of beef raised entirely on pasture is important, given that some analysts and consumers are calling for a shift to pasture beef finishing, or conversely that CAFO production is being adopted in other parts of the world.

Such a comparison would typically rely on life-cycle models, which would quantify global warming emissions and carbon sequestration from various practices used in each system. However, that approach presents substantial challenges. Conditions on actual farms that affect global warming emissions or carbon sequestration vary considerably: climate and geography greatly affect soils, precipitation, and types of pasture plants, for example. Management practices also vary widely—probably among pasture beef farms more than among CAFOs.

CAFO beef producers often have contracts with beef processors that require a uniform product that depends upon uniform practices. Feed distributors often mix grain grown under different conditions, so the concentrate reflects average crop productivity—in contrast to pasture crops, which vary widely. Finally, feedlot concentrates are composed largely of just a few types of feed grains, mainly corn, while different pastures host different species and combinations. Intensive corn breeding over many decades has produced feed corn that has uniform nutritional properties.

Modelers could include practices that may reduce the heat-trapping emissions of CAFOs, such as the use of anaerobic digesters to capture methane from manure, or the use of cover crops rotated with corn to reduce nitrogen pollution. However, those practices are not yet widely used commercially in the United States. Similarly, some newer practices for managing pastures may have superior properties, but land managers have not yet widely adopted them.

Another challenge in comparing the two systems for finishing beef is whether to consider promising practices not yet widely shown to be commercially viable, or that have geographic limitations. These include pasture species that require substantial precipitation and a temperate climate, and therefore could grow on only a subset of sites.

Finally, knowledge gaps make it difficult to quantify the heat-trapping emissions and carbon sequestration of all the practices and other factors at the farm level. As noted, for example, the impact of good management practices on carbon sequestration depends on land-use history, because that determines how much carbon the soil has already lost.

Variation in Important Aspects of Beef Production That Affect Global Warming Estimates

Evaluations comparing CAFOs and pasture beef show a range of outcomes. For example, one study found that CAFOs had a 30 percent smaller carbon footprint than pasture-finished beef. Those researchers used a value of zero—no change—for carbon sequestration on pasture (Pelletier, Pirog, and Rasmussen 2010). However, when those same researchers used a value of 0.4 Mg of carbon sequestration per hectare per year, they found that pastures had a 15 percent smaller carbon footprint than CAFOs.

Another study found that well-managed pastures in the U.S. Southeast sequestered 0.41 Mg of carbon per hectare per year (Conant, Six, and Paustian 2003), providing experimental support for the alternate sequestration value used by Pelletier and colleagues. However, yet another study found that just 13 million acres of pastureland could

Brian Prechtel, USDA-ARS

Grain-based concentrates fed to cattle in CAFOs promote fast weight gain. However, high-quality pasture forages can approximate the feed efficiency of grain concentrates, with the additional benefit of greater carbon storage under pasture compared with grain crops.

benefit from each of three practices designed to boost carbon sequestration (Lewandrowski et al. 2004).

Analysts' assumptions and findings about the rate at which cattle add weight—typically measured as average daily gain—also affect outcomes of studies comparing the climate change impact of CAFOs and pasture finishing. Higher ADG may substantially reduce the impact of pasture beef, for example, because that measure reflects the efficiency with which cattle digest forage, and higher efficiency means lower methane emissions. A higher ADG also means that cattle spend less time on pasture producing methane and nitrous oxide before slaughter.

Which figures for average daily weight gain do various analysts use when comparing the climate change impact of CAFOs and pasture beef finishing? Pelletier, Pirog, and Rassmusen used an ADG of 0.6 kg per day for pasture—only 43 percent of the 1.4 kg per day they found for concentrates used in CAFOs, based on data from Iowa (2010). Other analysts found a mean ADG of 1.49 kg per day for several breeds of bulls fed concentrate for 140 days (Chewning et al. 1990). However, DeRamus and colleagues found an ADG of 1.26 kg per day for cattle grazed on high-quality grasses in southern U.S. pasture—or 90 percent of the ADG for CAFOs found by Pelletier and colleagues.

In a study where cattle spent 140 days grazing on pasture composed of 60 percent alfalfa and about 30 percent bromegrass, McCaughey, Wittenberg, and Corrigan found that ADG was 1.07 to 1.48 kg per day. Meanwhile Marley et al. found that beef cattle on pasture with high-water-soluble carbohydrate ryegrass gained an average of 1.11 kg per day, while cattle on normal ryegrass gained just 0.89 kg per day.

Hart et al. predicted an ADG of 1.41 kg per day for heifers on high-quality perennial ryegrass (2009), but just 0.37 kg per day for heifers on poor-quality perennial ryegrass. Roberts et al. found an ADG of 1.04 for cattle in Alabama grazing on annual ryegrass, including a period of lower forage quality in spring, versus 1.20 for cattle fed concentrate (2009). If studies consider year-round weight gain for pasture beef, ADG could drop, given lower-quality forage during dormant periods. However, the use of high-quality harvested forage during dormant seasons may allow relatively high year-round ADG for pasture-finished beef (Table 2) (Rotz et al. 2005).

Beef cattle fed a diet in which 93 percent of metabolizable energy came from whole-plant corn silage attained an ADG of 1.07 kg per day (with the remaining 7 percent from soybean meal fortified with vitamins and minerals) (Brennan et al. 1987) (Table 2). Earlier research found an

TABLE 2. **Feed Efficiency of Forages Compared to Grain-Based Diet**

Feed Type	Forage Type	Average Daily Weight Gain (ADG, kg/day)	Feed Efficiency of Forage Compared to Concentrate Efficiency[a]	Feed Efficiency of Forage Compared to Mean Concentrate Efficiency[b]	Reference
Pasture		0.60			Pelletier et al. 2010
Concentrate[c]		1.40	0.43	0.44	
Concentrate		1.49			Chewning et al. 1990
Pasture	Bahiagrass, Bermudagrass and forbs overseeded with annual ryegrass	1.26		0.93	DeRamus et al. 2003
Pasture	60% alfalfa 30% bromegrass	1.07 and 1.48		0.79 and 1.09	McCaughey et al. 1997
Pasture	High-soluble-carbohydrate ryegrass	1.11		0.82	Marley et al. 2005
Pasture	Typical ryegrass	0.89		0.65	
Pasture	High-quality perennial ryegrass	1.41		1.04	Hart et al. 2009
Pasture	Low-quality perennial ryegrass	0.37		0.27	
Pasture	Perennial ryegrass	1.04	0.87	0.76	Roberts et al. 2009
Concentrate		1.20			
Harvested forage	Whole-plant corn silage	1.07		0.79	Brennan et al. 1987
Harvested forage	Pelleted alfalfa hay	1.05	0.83	0.77	Oltzen et al. 1971
Concentrate		1.27			
Harvested forage	Haylage[d]/corn silage	0.99	0.69	0.73	Young and Kauffman 1978
Harvested forage	Corn silage	1.09	0.76	0.80	
Concentrate		1.44			
Average pasture/ forage		***1.03***			
Avg. concentrate		***1.36***		***0.76***[e]	

a. Forage efficiency calculated as the ratio of forage feed efficiency (average daily gain, or ADG) to concentrate ADG, where the values for concentrate and forage come from the cited study.

b. Forage efficiency calculated as the ratio of forage feed efficiency (ADG) to concentrate ADG, where the value for forage comes from the cited study and the value for concentrate is the average from all cited studies (1.36 kg/day).

c. Concentrate refers to a grain-based feed, usually 80 to 85 percent grain, typically corn in the U.S. The study by Young and Kauffman used concentrate that was 66 percent corn.

d. Haylage is silage (see text) made from hay.

e. Average feed efficiency calculated as the ratio of the average efficiency of forage to the average efficiency of concentrate.

ADG of 1.05 kg per day for cattle fed pelleted alfalfa hay, compared with 1.27 for cattle fed concentrate (Oltjen, Rumsey, and Putnam 1971). Another study found ADGs of 0.99 kg per day, 1.09 kg per day, and 1.44 kg per day for a mixture of haylage/corn silage at 96 percent of diet, corn silage at 92 percent of diet, and a mixture of 66 percent corn/27 percent corn silage, respectively (Young and Kauffman 1978).

The values used by Pelletier, Pirog, and Rasmussen for ADG and percent of feed lost to methane emissions on pasture are within the range found by other researchers. The variations in ADG among the studies reflect differences in management practices that may be used on actual farms, and are acceptable values for models comparing the climate change impact of pasture-finished beef and CAFOs.

The average ADG for pasture or harvested forage from the nine studies in Table 2 is 1.03 kg per day—76 percent of the 1.36 average ADG for grain-based concentrates. Values for pasture or forage range from about 27 percent to more than 100 percent of the average ADG of concentrates.

This range of findings illustrates both the potential and the challenge of attaining the high ADG seen in some experimental pasture-raised beef systems. High cattle-growth rates are possible if producers can avoid grazing cattle on low-quality pasture—often when pasture is dormant. Researchers need to focus on extending the period of high-quality pasture growth through pasture species mixtures, management, and breeding of pasture crops.

Using high-quality stored forages such as pelleted alfalfa or silage is another possible solution to low ADG during periods when pasture is of low quality. The average ADG for stored forages in the four experiments in Table 2 was 1.05 kg per day, or 77 percent of the average ADG from concentrates. The former value is almost three times the lowest value for pasture forage, and 75 percent higher than the ADG for forage used by Pelletier and colleagues.

Earlier modeling, based largely on default factors for methane and nitrous oxide emissions from the Intergovernmental Panel on Climate Change (IPCC) in 1996, showed a much higher climate change impact from cow-calf operations than from feedlots per unit of production (Phettiplace, Johnson, and Sidel 2001). Much of the difference reflects differences in purpose between cow-calf operations and feedlots. During the period that cattle produce calves for cow-calf operations, they are not contributing directly to the beef supply, and therefore produce more global warming emissions than cattle fed only for slaughter.

That study showed that the use of intensive grazing reduced global warming emissions from cow-calf operations by 10 percent. That model also found that cow-calf operations lost 7 percent of feed energy to methane emissions, versus 3.5 percent for feedlots, based on dietary energy—a 100 percent difference. However, extensive modeling of factors contributing to methane emissions found that cattle eating high-quality forage lost 5.7 percent of feed energy to methane emissions, versus 4.7 percent for cattle fed concentrates used on feedlots—or only a 21 percent difference (Benchaar, Pomar, and Chiquette 2001).[10]

Despite the challenges entailed in comparing the climate change impact of CAFOs and pasture finishing systems, it is possible to identify several major advantages and disadvantages of these systems.

Pros and Cons of Pasture Finishing versus CAFOs

Perennial pasture species typically sequester more carbon in soil than annual row crops used for feed grain concentrates. On the other hand, cattle in CAFOs usually gain weight faster than cattle on pasture. The result is that feedlots may produce fewer methane and nitrous oxide emissions per unit of product, but pastures may offset that advantage by sequestering more carbon in the soil.

However, best management practices can affect both the rate at which pasture soil sequesters carbon and the rate at which pasture plants grow—and thus the productivity of beef production—as well as other factors that influence methane and nitrous oxide emissions from pasture.

Carbon Sequestration in Soil

One review found a mean value for carbon sequestration by U.S. annual crops, given best management practices—including no-till farming—of about 0.57 Mg of carbon per hectare per year (West and Post 2002). Other studies

10 The use of intensive grazing may have improved forage quality as well as other factors in Phettiplace (2001). The findings from Benchar are most relevant for comparing practices within that study rather than between studies.

of different U.S. regions or different periods of time found values for no-till farming of -0.07 (loss of carbon), 0.10, 0.22, 0.27, 0.30, 0.45, and 0.48 Mg of carbon per hectare per year (references in Franzleubbers 2010).

However, researchers have recently questioned the efficacy of no-till versus plowing for carbon sequestration, based on an analysis of deeper soil horizons (Poirier et al. 2009; Blanco-Canqui and Lal 2008; Baker et al. 2007). If sequestration rates are lower for grain crops under no-till than in the studies above, the options for reducing the climate impact of feedlots may be more limited than previously thought.

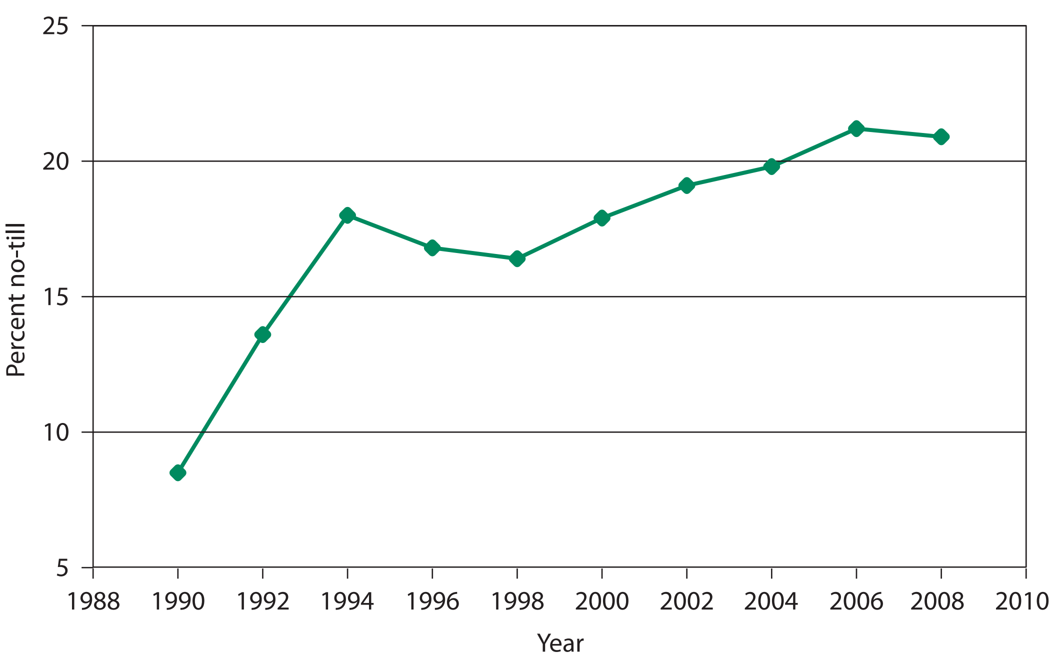
By comparison, as noted in Chapter 5, several studies show carbon sequestration rates on well-managed pasture ranging from 0.3 to 0.84 Mg of carbon per hectare per year. One review of studies from the U.S. Northwest and western Canada found that reclaimed mine sites and cropland converted to grassland sequestered a mean of 0.94 Mg of carbon per hectare per year (Liebig et al. 2005). Another review of cropland converted to pasture found increased sequestration of 1.01 Mg of carbon per hectare per year (Conant, Paustian, and Elliott 2001).

A recent study directly compared root and carbon properties—indirect indicators of carbon sequestration—of native Kansas grassland before and after conversion to no-till row crops. Root biomass dropped 43 percent, and the amount of readily metabolized carbon—a measure of soil carbon—fell after three years (DuPont et al. 2010).

Although overall carbon sequestration rates for well-managed pasture are sometimes close to double those of no-till annual crops, according to these studies, analysts and policy makers must use caution when generalizing these results. Management practices and other farm conditions can greatly affect sequestration rates. And many carbon sequestration studies last fewer than 5 or 10 years, which may make the results more variable (Franzleubbers 2010; Six et al. 2004). Longer-term studies could evaluate the sequestration benefits of practices for managing pastures and annual crops more accurately (Six et al. 2004).

If carbon sequestration differs between tilled and no-till fields, then estimates of the climate impact of feedlot-based finishing systems must account for the amounts of corn—the primary component of feed for feedlots—grown with and without tillage. Surveys by the Conservation Technology Information Center show a substantial increase in the percentage of corn acreage farmed by no-till methods in the early 1990s, but only small percentage gains since. As of 2008, only about 21 percent of corn acres were under no-till (Figure 3) (Conservation Technology Information Center 2010).

FIGURE 3. No-Till Acreage Devoted to Corn in the United States



Source: Conservation Technology Information Center 2010.

According to the U.S. Department of Agriculture, 23.5 percent of no-till acres were devoted to corn in 2005, and 23.5 to 29.5 percent in 2009 (Horowitz, Ebel, and Ueda 2010). The percentage of no-till corn has therefore increased by only 5 to 8 percent since the mid-1990s, despite policy incentives and technologies such as seeding equipment that facilitate no-till farming.

These findings suggest that farmers may have reasons to limit no-till practices on corn acres. For example, soils warm more slowly and stay wet longer when not tilled. Those factors limit initial crop growth rates and can require a longer growing season, which is often undesirable in many areas. The crop residues that remain on the soil under no-till farming may also harbor some insect and disease organisms.

Methane Emissions

As noted, comparisons between pasture forage and concentrates usually show higher feed efficiency for grain-based concentrates. Higher feed efficiency means cattle on feedlots have less enteric fermentation, and therefore produce fewer methane emissions. Higher feed efficiency also means that cattle take less time to gain the desired amount of weight—and therefore have less time to produce methane emissions.

The rumen converts starch—a primary component of corn not found in forage—to metabolic energy more efficiently than the non-structural carbohydrates found in high-quality forages such as sugars. Because of this advantage, beef producers relying on pasture finishing typically do not achieve the same level of feed efficiency as corn-based feedlots, even with better-quality forage.

As noted, Benchaar, Pomar, and Chiquette found that cattle fed fresh alfalfa—the best forage tested—lost 21 percent more food energy to methane emissions than cattle fed concentrates (2001). However, models have not widely compared the climate change impact of concentrates with combinations of forages, or forage species shown to increase feed efficiency and reduce methane emissions on pasture, such as birdsfoot trefoil.

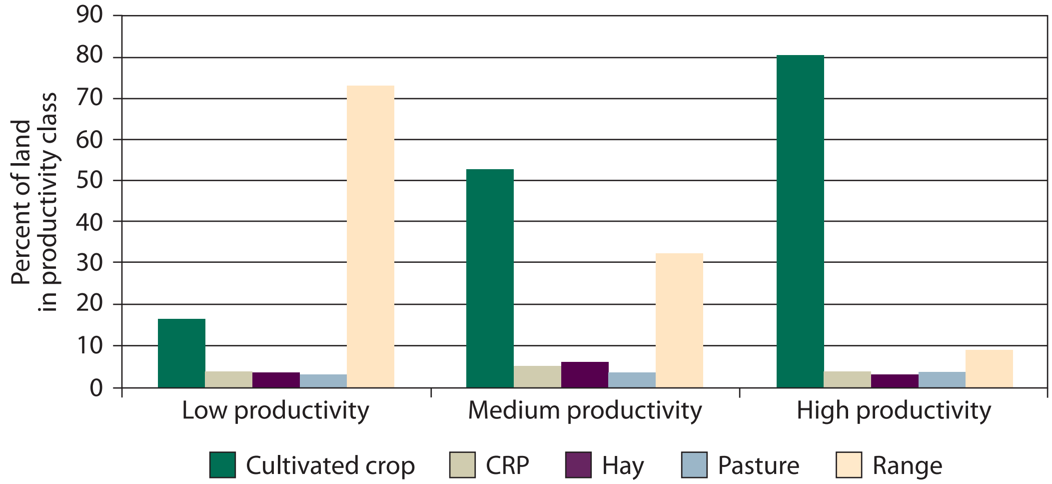
Methane emissions from manure occur largely under anaerobic conditions. Because manure from cattle in CAFOs often has relatively low water content, it is less likely to be anaerobic than manure from dairy cows or pigs in CAFOs, which is typically stored in slurry form in lagoons or pits. Dung deposited on pasture is largely aerobic. However, because the feed efficiency of beef cattle on pasture is lower, they produce manure over a longer period of time than cows on feedlots.

Nitrous Oxide Emissions

When actual measurements of emissions are not available, the IPCC assumes that 1 percent of applied synthetic nitrogen—or nitrogen from manure or crop residue such as

Bob Nichols, USDA-NRCS

FIGURE 4. **Land Use by Productivity Level, U.S. Northern Plains Region**



Source: Claassen, Carriazo, and Ueda 2010.

Note: CRP = Conservation Reserve Program.

legumes—is lost as nitrous oxide emissions (2006). However, as with methane production, cattle on pasture may produce more nitrous oxide emissions than cattle in feedlots, given the longer time pasture-finished cattle require to gain the desired weight.

As noted, a particular challenge for pasture beef finishing is the high concentration of nitrogen in urine patches—often 1,000 kg per hectare within the patch—which can be readily converted to nitrous oxide. That amount is higher than the typical application rates of synthetic nitrogen fertilizer, although manure typically covers considerably less than an entire pasture.

As Chapter 4 also noted, several practices are available to reduce the impact of urine patches. These include increasing the amount of nitrogen in forage that cattle absorb during digestion, shifting nitrogen from urine to dung, capturing some manure off-pasture and distributing it uniformly on pasture, using denitrification inhibitors, and encouraging more uniform deposition on pastures. It is unclear how great an effect these practices would have, because measurements on farms have been limited.

In theory, CAFO beef producers can distribute manure on farmland to avoid the kind of high nitrogen concentrations found in urine patches on pasture. However, in practice that is often difficult to achieve (Gurian-Sherman 2008). The very large amount of manure from as many as tens of thousands of cattle on a CAFO can be costly to distribute to enough farmland to avoid over-fertilization from nitrogen or phosphorus. All beef producers also face fundamental tradeoffs between applying enough nitrogen to maximize the productivity of feed crops and forage while minimizing nitrous oxide emissions and other forms of nitrogen pollution.

Land Productivity

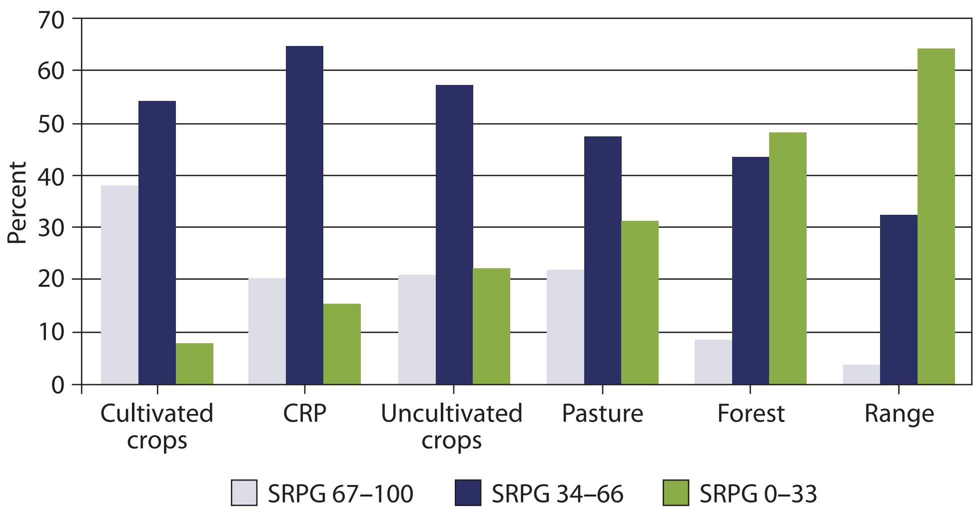
The productivity, or fertility, of land also affects the climate change impact of pasture versus CAFO finishing, because it influences the amount of primary biomass—pasture or grain crops—that grows on it, and thus the amount of beef produced per unit of land area. Faster-growing crops on more productive land also absorb more nitrogen from soil, reducing nitrous oxide emissions. And land that is more productive can sequester more carbon per year because it has more primary biomass input—or more manure input—because it can sustain higher stocking densities. However, where higher fertility means that the land has lost little carbon, the duration of additional sequestration may be reduced compared to some less-fertile land.

U.S. farmers usually grow feed grain and other cultivated crops on land that is more productive than that devoted to pasture. For example, in northern plains states, most highly and moderately productive land supports cultivated crops, while most low and moderately productive land is used as pasture and range, and to grow hay for ruminant forage (Figure 4) (Claassen, Carriazo, and Ueda 2010).

At the national level, nearly 95 percent of cultivated crops grow on soil of moderate to high productivity, compared to just 70 percent of pasture. And nearly twice as much cropland as pastureland is highly productive. Only about 5 percent of cultivated crops—versus 30 percent of pasture—grow on low-productivity soil (Figure 5) (Lubowski et al. 2002).

Comparisons of the global warming impact of pasture beef and CAFOs need to account for underlying differences in the quality of land typically devoted to pasture and grain crops in the United States. Most grain crop production occurs on higher-quality land than most pasture beef production. Most analysts have not considered land quality when comparing the global warming emissions of pasture beef finishing and CAFOs, and that may lead them to overestimate the climate impact of the former.

FIGURE 5. Agricultural Use by Soil Productivity Level, 1982–1997



Source: Lubowski et al. 2002.

Note: SRPG = soil rating for plant growth. Higher-rated soil is more productive.

CHAPTER 7

Conclusions and Recommendations

Pasture and rangeland will continue to be mainstays of beef production because ruminants must consume some forage to stay healthy, and because they can produce high-quality food from low-quality grassland that cannot support crops. Some consumers may also prefer beef produced exclusively on pasture. Developing and implementing practices that reduce the climate impact of pasture beef production is therefore important.

U.S. beef producers can reduce their heat-trapping emissions and increase soil carbon sequestration by using best practices for managing pastures available now. These improved practices will have a small impact on overall U.S. global warming emissions, but will significantly curb other serious pollution caused by beef production. The improved practices include:

- Increasing the percentage of legumes in forage mixtures.
- Using moderate cattle stocking densities without overgrazing, possibly in conjunction with managed rotational grazing.
- Avoiding the use of low-quality, mature pasture to graze cattle or as a source of stored forage.
- Avoiding excessive use of nitrogen fertilizer.

However, policy makers and beef producers need more information on several of these practices—especially rotational grazing—to have confidence in them. Beef producers also need more information on local soil and climate conditions and pasture species to decide how to maximize productivity while minimizing global warming emissions and increasing carbon sequestration.

Other practices that show promise for reducing the climate change impact of pasture beef (but need more research) include:

- Adding legumes that produce beneficial types of condensed tannins, such as birdsfoot trefoil, to pastures.

- Encouraging more even deposition of manure on pastures by moving water and shelter sources, and using smaller paddocks.
- Using nitrification inhibitors to reduce nitrous oxide emissions from urine patches.

In the longer term, the breeding of better pasture crops could enable cattle to use nitrogen more efficiently and grow faster, reducing methane and nitrous oxide emissions. Plant breeders could also improve the efficiency with which pasture plants use nitrogen and increase their biomass, enabling pasture soils to sequester more carbon.

For beef producers not committed to keeping cattle exclusively on pasture, other options for reducing heat-trapping emissions include:

- Allowing cattle to graze on pasture just four to eight hours a day, to reduce uneven, high-concentration manure deposition.
- Relying on high-quality harvested forage, such as silage or alfalfa pellets, to avoid grazing cattle on mature, low-quality pasture in summer and late fall, and in winter in northern areas, when pastures are dormant.
- Collecting manure when cattle are off pasture for more uniform distribution on pastures or row crops.

The Climate Impact of Pasture Finishing versus CAFOs

Comparing pasture and CAFO finishing systems is difficult because practices and conditions vary between farms, particularly in pasture systems. That makes choosing which com-binations of practices to analyze challenging, especially choosing widely accepted practices versus those that show promise. Information on the heat-trapping emissions from different practices is sometimes inadequate, and may vary geographically owing to differences in soil and climate.

Global warming emissions and factors that affect them, as well as carbon sequestration, can also vary considerably between experiments and practices, so analysts and farmers should use caution when considering the results of modeling. Whole-farm studies—such as life-cycle analyses—could help analysts account for all global warming emissions from beef production systems. That approach could be especially valuable in evaluating practices for which little information on emissions is now available, such as rotational grazing.

Recent comparisons illustrate this difficulty. For example, Pelletier, Pirog, and Rasmussen found that the rate of carbon sequestration they chose affected the climate change impact of pasture versus feedlot systems (2010)—with either of two values plausible for different farms. Global warming emissions from forage can also vary considerably, depending on the share converted to methane through enteric fermentation.

Feedlots and pasture have different strengths for reducing climate impact. Concentrates used for feedlots—primarily corn—are of uniformly high quality, and their high starch content allows cattle to gain weight rapidly. Those attributes mean less feed energy is lost to methane emissions. The rapid growth rate stemming from concentrate also means less time to slaughter—and therefore lower methane and nitrous oxide emissions per unit of beef.

Even with better breeding, pasture forages are unlikely to consistently match the efficiency of concentrates, because starch is more efficient as feed than the non-structural carbohydrates found in forages. However, feed efficiency can vary considerably among different forages, which in turn can affect the overall climate impact of pasture versus feedlots.

The highest feed efficiencies of forage reported in published studies are close to or match the average feed efficiency of concentrates. This suggests that optimization of forage nutritional quality could substantially reduce the current feed efficiency advantage of CAFOs.

Pasture soils that support perennial species often sequester considerably more carbon, even doubling the amount compared with row crops grown without tillage, such as corn (the main component of CAFO concentrates). And only about 20 percent of U.S. acreage devoted to corn is no-till. Despite technological innovations and incentives to encourage the use of that approach, the share of corn acreage devoted to no-till has remained about the same over the past 15 years. Corn acres that rely on some tillage may sequester less carbon than no-till acres—and much less than well-managed perennial pasture.

When comparing the climate impact of pasture and feedlots, analysts and beef producers also need to consider policies and other factors that may skew outcomes. For example, the productivity of land affects crop productivity, heat-trapping emissions, and carbon sequestration. And in the United States, crops are much more likely than pasture plants to grow on highly productive land.

Curbing Other Pollution from Beef Production

While beef production contributes significantly to U.S. heat-trapping emissions, it may play an even larger role collectively in other forms of pollution, such as air pollution from ammonia and eutrophication of coastal waters. Policy makers should not encourage practices that reduce the global warming emissions and boost the carbon sequestration of pasture beef while worsening other environmental and social effects.

Fortunately, many practices that reduce the climate change impact of beef production also curb other pollution. For example, practices that reduce nitrogen concentration in soil from manure and fertilizer also curb other forms of nitrogen pollution.

However, some tradeoffs between heat-trapping emissions and other negative effects of beef production seem likely. For example, beef cattle finished in feedlots require more antibiotic use than pasture-raised cattle, producing more antibiotic-resistant human pathogens (Gurian-Sherman 2008).

Overall, beef producers face challenges in deciding which practices to adopt, given variations in local conditions and myriad potential practices. Agricultural extension scientists and model farms could be critical in helping beef producers achieve high productivity while minimizing their climate impact.

Recommendations

The federal farm bill and other policy mechanisms offer substantial opportunities to reduce the climate change impact of pasture beef production. The following recommendations would improve our understanding of the potential for best practices to curb the heat-trapping emissions and boost the carbon sequestration of pasture beef, and spur the use of those practices:

1. The U.S. Department of Agriculture (USDA) should expand its research on global warming emissions from pasture beef production, and further develop management practices to curb those emissions. Critical needs include:

- Breeding and development of other practices to promote more nutritious pasture crops.
- Investigating the most effective combinations of climate-friendly practices.
- Improving the ability of high-quality legumes to become established and to persist in mixed pastures.
- Improving the efficiency with which pasture crops use nitrogen.

- Boosting forage yields and extending the period of high-quality pasture growth.
- Collecting information on practices now used to manage the quality of pastures and the amount of carbon in various soils.
- Optimizing intensive rotational grazing systems and investigating their impact on methane and nitrous oxide emissions and long-term carbon sequestration.
- Pursuing whole-farm studies of suites of climate-friendly practices to identify synergies, optimize carbon budgets, and evaluate any tradeoffs.
- Developing demonstration projects and educational materials to alert cow-calf operators and pasture beef producers to the advantages of better pasture management.

2. The USDA's Natural Resources Conservation Service should expand its efforts to encourage best management practices that reduce methane and nitrous oxide emissions and boost carbon sequestration. This work should include:

- Using the Conservation Stewardship Program to provide incentive payments for:
  - Practices that may reduce methane and nitrous oxide emissions, including increasing the share of legumes and improved forage crops in forage mixtures, using moderate cattle stocking densities, using appropriate amounts of synthetic fertilizer, avoiding grazing cattle on low-quality mature pasture—such as by substituting high-quality stored forages—and encouraging more even distribution of manure on pastures.
  - Practices that increase carbon sequestration, such as supplying the precise amount of nutrients that crops need from legume species, manure, or synthetic fertilizer, and preventing overgrazing.
- Providing technical assistance to beef producers to help and encourage them to implement such practices.
- Providing transitional support through the Environmental Quality Incentives Program to beef producers that switch from confinement to pasture-based finishing systems that use best management practices.

3. State- and federally funded university extension services should advise and train beef producers on climate-friendly practices, including use of the highest-quality forage, and strategies to prevent overgrazing.

REFERENCES

Anderson, N., R. Strader, and C. Davidson. 2003. Airborne reduced nitrogen: Ammonia emissions from agriculture and other sources. *Environment International* 29:277–286.

Baker, J.M., T.E. Ochsner, R.T. Venterea, and T.J. Griffis. 2007. Tillage and soil carbon sequestration—What do we really know? *Agriculture, Ecosystems and Environment* 118:1–5.

Benchaar, C., C. Pomar, and J. Chiquette. 2001. Evaluation of dietary strategies to reduce methane production in ruminants: A modelling approach. *Canadian Journal of Animal Science* 81:563–574.

Beuselinck, P.R., E.C. Brummer, D.K. Viands, K.H. Asay, R.R. Smith, J.J. Steiner, and D.K. Brauer. 2005. Rhizomatous *Lotus corniculatus*: V. genotypic and environmental effects on growth. *Crop Science* 45:1736–1740.

Blanco-Canqui, H., and R. Lal. 2008. No-tillage and soil-profile carbon sequestration: An on-farm assessment. *Soil Science Society of America Journal* 72:693–701.

Boadi, D., C. Benchaar, J. Chiquette, and D. Massé. 2004. Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review. *Canadian Journal of Animal Science* 84:319–335.

Boody, G., B. Vondracek, D. Andow, M. Krinke, J. Westra, J. Zimmerman, and P. Welle. 2005. Multifunctional agriculture in the United States. *Bio-Science* 55(1):27–38.

Bregard, A., G. Belanger, and R. Michaud. 2000. Nitrogen use efficiency and morphological characteristics of timothy populations selected for low and high forage nitrogen concentrations. *Crop Science* 40:422–429.

Brennan R.W., M.P. Hoffman, F.C. Parrish, F. Epplin, O. Bhide, and E.O Heady. 1987. Effects of differing ratios of corn silage and corn grain on feedlot performance, carcass characteristics and projected economic returns. *Journal of Animal Science* 64:23–31.

Burkart, M., D. James, M. Liebman, and C. Herndl. 2005. Impacts of integrated crop-livestock systems on nitrogen dynamics and soil erosion in western Iowa watersheds. *Journal of Geophysical Research* 110:G01009, doi:10.1029/2004JG000008.

Casler, M.D., and E.C. Brummer. 2008. Theoretical expected genetic gains for among-and-within-family selection methods in perennial forage crops. *Crop Science* 48:890–902.

Cassman, K.G., A. Dobermann, D.T. Walters, and H. Yang. 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. *Annual Review of Environment and Resources* 28:315–358.

Chewning, J.J., A.H. Brown, Jr., Z.B. Johnson, and C.J. Brown. 1990. Breed means for average daily gain, feed conversion and intake of beef bulls during postweaning feedlot performance tests. *Journal of Animal Science* 68:1500–1504.

Claassen, R., F. Carriazo, and K. Ueda. 2010. Grassland conversion for crop production in the United States: Defining indicators for policy analysis. Paris: Organisation for Economic Co-operation and Development. Online at *http://www.oecd.org/dataoecd/31/22/44807867.pdf.*

Clancy K. 2006. *Greener pastures: How grass-fed beef and milk contribute to healthy eating*. Cambridge, MA: Union of Concerned Scientists.

Conant, R.T., K. Paustian, and E.T. Elliott. 2001. Grassland management and conversion into grassland: Effects on soil carbon. *Ecological Applications* 11(2):343–355.

Conant, R.T., J. Six, and K. Paustian. 2003. Land use effects on soil carbon fractions in the southeastern United States: Management-intensive versus extensive grazing. *Biology and Fertility of Soils* 38:386–392.

Conner R., A. Seidl, L. VanTassell, and N. Wilkins. 2001. United States grasslands and related resources: An economic and biological trends assessment. Online at *http://irnr.tamu.edu/pdf/grasslands_high.pdf.*

Conservation Technology Information Center. 2010. Crop residue management. Online at *www.ctic.purdue.edu/crm_results*.

Deak, A., M.H. Hall, and M.A. Sanderson. 2007. Production and nutritive value of grazed simple and complex forage mixtures. *Agronomy Journal* 99:814–821.

DeRamus, H.A., T.C. Clement, D.D. Giampola, and P.C. Dickison. 2003. Methane emissions of beef cattle on forages: Efficiency of grazing management systems. *Journal of Environmental Quality* 32:269–277.

Dewhurst, R.J., L. Delaby, A. Moloney, T. Boland, and E. Lewis. 2009. Nutritive value of forage legumes used for grazing and silage. *Irish Journal of Agricultural and Food Research* 48:167–187.

DuPont, S.T., S.W. Culman, H. Ferris, D.H. Buckley, and J.D. Glover. 2010. No-tillage conversion of harvested perennial grassland to annual cropland reduces root biomass, decreases active carbon stocks, and impacts soil biota. *Agriculture, Ecosystems and Environment* 137:25–32.

Environmental Protection Agency (EPA). 2010. Inventory of U.S. greenhouse gas emissions and sinks, 1990–2010. No. 430-R-10-006. Washington, DC.

EPA. 2009. Inventory of U.S. greenhouse gas emissions and sinks, 1990–2007. No. 430-R-09-004. Washington, DC.

EPA. 2005. National emission inventory: Ammonia emissions from animal husbandry operations. Online at *ftp://ftp.epa.gov/EmisInventory/2002finalnei/documentation/nonpoint/nh3inventory_draft_042205.pdf*.

Eshel, G., and P.A. Martin. Diet, energy and global warming. *Earth Interactions* 10:1–17.

Fisher, M.J., I.M. Tao, M.A. Ayarza, C.E. Lascano, J.I. Sanz, R.J. Thomas, and R.R. Vera. 1994. Carbon storage by introduced deep-rooted grasses in the South American savannas. *Nature* 371:236–238.

Follett R.F., J.M. Kimble, and R. Lal. 2001. The potential of U.S. grazing lands to sequester soil carbon. In *The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect*, edited by R.F. Follett, J.M. Kimble, and R. Lal. CRC Press.

Follett, R.F., and D.A. Reed. 2010. Soil carbon sequestration in grazing lands: Social benefits and policy implications. *Rangeland Ecology and Management* 63:4–15.

Franzluebbers, A.J. 2010. Achieving soil organic carbon sequestration with conservation agricultural systems in the southeastern United States. *Soil Science Society of America Journal* 74(2):347–357.

Franzluebbers, A.J., and J.A. Stuedemann 2009. Soil-profile organic carbon and total nitrogen during 12 years of pasture management in the Southern Piedmont USA. *Agriculture, Ecosystems and Environment* 129:28–36.

Frey, K.J. 1996. National plant breeding study. Special report 98. Ames, IA: Iowa State University. Online at *http://www.ers.usda.gov/data/plantbreeding/Plant%20Breeding.pdf*.

Frolking S.E., A.R. Mosier, D.S. Ojima, C. Li, W.J. Parton, C.S. Potter, E. Priesack, R. Stenger, C. Haberbosch, P. Dörsch, H. Flessa, and K.A. Smith. 1998. Comparison of N_2O emissions from soils at three temperate agricultural sites: Simulations of year-round measurements by four models. *Nutrient Cycling in Agroecosystems* 52:77–105.

Gewin, V. 2010. An underground revolution. *Nature* 466:552–553.

Giltrap, D.L, J. Singh, S. Saggar, and M. Zaman. 2010. A preliminary study to model the effects of a nitrification inhibitor on nitrous oxide emissions from urine-amended pasture. *Agriculture, Ecosystems and Environment* 136:310–317.

Goolsby, D.A.,W.A. Battaglin, G.B. Lawrence, R.S. Artz, B.T. Aulenbach, R.P. Hooper, D.R. Keeney, and G.J. Stensland. 1999. Flux and sources of nutrients in the Mississippi-Atchafalaya River Basin. Topic paper no. 3, NOAA Coastal Ocean Program decision analysis series no. 17. Washington, DC: National Oceanic and Atmospheric Administration.

Goodland R. 1997. Environmental sustainability in agriculture: Diet matters. *Ecological Economics* 23:189–200.

Graham P.H., and C.P. Vance. 2003. Legumes: Importance and constraints to greater use. *Plant Physiology* 131:872–877.

Gurian-Sherman, D. 2008. *CAFOs uncovered: The untold costs of confined animal feeding operations*. Cambridge, MA: Union of Concerned Scientists.

Hart K.J., P.G. Martin, P.A. Foley, D.A. Kenny, and T.M. Boland. 2009. Effect of sward dry matter digestibility on methane production, ruminal fermentation, and microbial populations of zero-grazed beef cattle. *Journal of Animal Science* 87:3342–3350.

Haynes, R.J., and P.H. Williams. 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. *Advances in Agronomy* 49:119–199.

Horowitz J., R. Ebel, and K. Ueda. 2010. "No-till" is a growing practice. Economic information bulletin no. 70. Washington, DC: U.S. Department of Agriculture, Economic Research Service.

Houghton R.A., J.L. Hackler, and K.T. Lawrence. 1999. The U.S. carbon budget: Contributions from land-use change. *Science* 285(5427):574–578.

Howarth, R.E., R.K. Chaplin, K.-J. Cheng, B.P. Goplen, J.W. Hall, R. Hironaka,W. Majak, and O.M. Radostits. 1991. *Bloat in cattle*. Publication no. 1858. E. Ottawa, Ontario: Agriculture Canada.

Howieson, J.G., G.W. O'Hara, and S.J. Carr. 2000. Changing roles for legumes in Mediterranean agriculture: Developments from an Australian perspective. *Field Crops Research* 65:107–122.

Hyatt, C.R., R.T. Venterea, C.R. Rosen, M. McNearney, M.L. Wilson, and M.S. Dolan. 2010. Polymer-coated urea maintains potato yields and reduces nitrous oxide emissions in a Minnesota loamy sand. *Soil Science Society of America Journal* 74(2):419–428.

Intergovernmental Panel on Climate Change (IPCC), Task Force on National Greenhouse Gas Inventories. 2006. 2006 IPCC guidelines for national greenhouse gas inventories, edited by H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe. Tokyo: Institute for Global Environmental Strategies.

Johnson, D.E., G.W. Ward, and J.J. Ramsey. 1996**.** Livestock methane: Current emissions and mitigation potential. In *Nutrient management of food animals to enhance and protect the environment*, edited by E.T. Kornegay. New York, NY: Lewis Publishers.

Kirchmann, H., and E. Witter. 1992. Composition of fresh, aerobic and anaerobic farm animal dungs. *Bioresource Technology* 40:137–142.

Lal, R., R.F. Follett, B.A. Stewart, and J.M. Kimble. 2007. Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science* 172(12):943–956.

Ledgard, S.F. 1991. Transfer of fixed nitrogen from white clover to associated grasses in swards grazed by dairy cows, estimated using 15N methods. *Plant and Soil* 131:215–223.

Ledgard, S.F., J.W. Penno, and M.S. Sprosen. 1999. Nitrogen inputs and losses from clover/grass pastures grazed by dairy cows, as affected by nitrogen fertilizer application. *Journal of Agricultural Science* 132:215–225.

Lee, J.J., and R. Dodson. 1996. Potential carbon sequestration by afforestation of pasture in the South-Central United States. *Agronomy Journal* 88:381–384.

Lewandrowski, J., C. Jones, R. House, M. Peters, M. Sperow, M. Eve, and K. Paustian. 2004. Economics of sequestering carbon in the U.S. agricultural sector. Technical bulletin no. 1909. Washington, DC: U.S. Department of Agriculture, Economic Research Service.

Liebig, M.A., J.A. Morgan, J.D. Reeder, B.H. Ellert, H.T. Gollany, and G.E. Schuman. 2005. Greenhouse gas contributions and mitigation potential of agricultural practices in northwestern USA and western Canada. *Soil & Tillage Research* 83:25–52.

Linn, D.M., and J.W. Doran. 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Science Society of America Journal* 48:1267–1272.

Lubowski, R.N, M. Vesterby, S. Bucholtz, A. Baez, and M.J. Roberts. 2002. Major uses of land in the United States, 2002. EIB-14, Washington, DC: U.S. Department of Agriculture, Economic Research Service.

MacAdam, J.W, T.C. Griggs, P.R. Beuselinck, and J.H. Grabber. 2006. Birdsfoot trefoil, a valuable tannin-containing legume for mixed pastures. *Forage and Grazinglands* doi:10.1094/FG-2006-0912-01-RV.

Marley, C.L., D.A. Davies, J.E. Vale, J.G. Evans, N.D. Scollan, J.M. Moorby, J.C. MacRae, and M.K. Theodorou. 2005. Effects of upland pastures sown with two contrasting *Lolium perenne* varieties on the performance of beef steers when compared to steers grazing permanent pastures. *Proceedings of the British Society for Animal Science*, *Annual Conference 2005*.

Mathews, K.H., Jr., and R.J. Johnson. 2010. *Grain and grass beef production systems*. In *Livestock and poultry outlook*, edited by R.J. Johnson. LDP-M-192. Washington, DC: U.S. Department of Agriculture, Economic Research Service.

McCaughey, W.P., K. Wittenberg, and D. Corrigan. 1997. Methane production by steers on pasture. *Canadian Journal of Animal Science* 77:519–524.

Miller, L.A., J.M. Moorby, D.R. Davies, M.O. Humphreys, N.D. Scollan, J.C. MacRae, and M.K. Theodorou. 2001. Increased concentration of water-soluble carbohydrate in perennial ryegrass (*Lolium perenne* L.): Milk production from late-lactation dairy cows. *Grass and Forage Science* 56:383–394.

Min, B.R., T.N. Barry, G.T. Attwood, and W.C. McNabb. 2003. The effect of condensed tannins on the nutrition and health of ruminants fed fresh temperate forages: a review. *Animal Feed Science and Technology* 106:3—19.

Min, B.R., W.E. Pinchak, R.C. Anderson, J.D. Fulford, and R. Puchala. 2006. Effects of condensed tannins supplementation level on weight gain and in vitro and in vivo bloat precursors in steers grazing winter wheat. *Journal of Animal Science* 84:2546–2554.

Moorby, J.M., R.T. Evans, N.D. Scollan, J.C. MacRae, and M.K. Theodorou. 2006. Increased concentration of water-soluble carbohydrate in perennial ryegrass (*Lolium perenne* L.): Evaluation in dairy cows in early lactation. *Grass and Forage Science* 61:52–59.

Mourino, F., K.A. Albrecht, D.M. Schaefer, and P. Berzaghi. 2003. Steer performance on kura clover–grass and red clover–grass mixed pastures. *Agronomy Journal* 95:652–659.

National Research Council. 2010. *The impact of genetically engineered crops on farm sustainability in the United States*. Washington, DC: National Academies Press.

Ogle, S.M, R.T. Conant, and K. Paustian. 2004. Deriving grassland management factors for a carbon accounting method developed by the Intergovernmental Panel on Climate Change. *Environmental Management* 33(4):474–484.

Oltjen R.R., T.S. Rumsey, and P.A. Putnam. 1971. All-forage diets for finishing beef cattle. *Journal of Animal Science* 32: 327–333.

Owens, F.N, D.S. Secrist, W.J. Hill, and D.R. Gill. 1998. Acidosis in cattle: A review. *Journal of Animal Science* 76:275–286.

Owens, L.B., M.W. Edwards, and R.W. Van Keurcn. 1994. Groundwater nitrate levels under fertilized grass and grass-legume pastures. *Journal of Environmental Quality* 23:752–758.

Pelletier N., R. Pirog, and R. Rasmussen. 2010. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. *Agricultural Systems* doi:10.1016/j.agsy.2010.03.009.

Phetteplace, H.W., D.E. Johnson, and A.F. Seidl. 2001. Greenhouse gas emissions from simulated beef and dairy livestock systems in the United States. *Nutrient Cycling in Agroecosystems* 60:99–102.

Picasso, V.D., E.C. Brummer, M. Liebman, P.M. Dixon, and B.J. Wilsey. 2008. Crop species diversity affects productivity and weed suppression in perennial polycultures under two management strategies. *Crop Science* 48:331–342.

Poirier, V., D.A. Angers, P. Rochette, M.H. Chantigny, N. Ziadi, G. Tremblay, and J. Fortin. 2009. Interactive effects of tillage and mineral fertilization on soil carbon profiles. *Soil Science Society of America Journal* 73:255–261.

Puchala, R., B.R. Min, A.L. Goetsch, and T. Sahlu. 2010. The effect of a condensed tannin-containing forage on methane emission by goats. *Journal of Animal Science* 83:182–186.

Ravishankara, A.R., J.S. Daniel, and R.W. Portmann. 2009. Nitrous oxide (N_2O): The dominant ozone-depleting substance emitted in the 21st century. *Science* Express doi:10.1126/science. 1176985.

Roberts, S.D., C.R. Kerth, K.W. Braden, D.L. Rankins, Jr., L. Kriese-Anderson, and J.W. Prevatt. 2009. Finishing steers on winter annual ryegrass (*Lolium multiflorum* Lam.) with varied levels of corn supplementation I: Effects on animal performance, carcass traits, and forage quality. *Journal of Animal Science* 87:2690–2699.

Robertson, L.J., and G.C. Waghorn. 2002. Dairy industry perspectives on methane emissions and production from cattle fed pasture or total mixed rations in New Zealand. *Proceedings of the New Zealand Society of Animal Production* 62:213–218.

Rockström, J., W. Steffen, K. Noone, Å. Persson, F.S. Chapin III, E.F. Lambin, T.M. Lenton, M. Scheffer, C. Folke, H.J. Schellnhuber, B. Nykvist, C.A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P.K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R.W. Corell, F.J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J.A. Foley. 2009. A safe operating space for humanity. *Nature* 461:472–475.

Rotz, C.A., F. Taube, M.P. Russelle, J. Oenema, M.A. Sanderson, and M. Wachendorf. 2005. Whole-farm perspectives of nutrient flows in grassland agriculture. *Crop Science* 45:2139–2159.

Russelle, M.P., M.H. Entz, and A.J. Franzluebbers. 2007. Reconsidering integrated crop-livestock systems in North America. *Agronomy Journal* 99:325–334.

Saggar, S., R.M. Andrew, K.R. Tate, C.B. Hedley, N.J. Rodda, and J.A. Townsend. 2004a. Modelling nitrous oxide emissions from dairy-grazed pastures. *Nutrient Cycling in Agroecosystems* 68:243–255.

Saggar, S., N.S. Bolan, R. Bhandral, C.B. Hedley, and J. Luo. 2004b. A review of emissions of methane, ammonia, and nitrous oxide from animal excreta deposition and farm effluent application in grazed pastures. *New Zealand Journal of Agricultural Research* 47:513–544.

Sanderson, M. 2010. Nutritive value and herbage accumulation rates of pastures sown to grass, legume and chicory mixtures. *Agronomy Journal* 102 (2):728–733.

Sanderson, M.A., K.J. Soder, L.D. Muller, K.D. Klement, R.H. Skinner, and S.C. Goslee. 2005. Forage mixture productivity and botanical composition in pastures grazed by dairy cattle. *Agronomy Journal* 97:1465–1471.

Sauer, T.J., S.R. Compston, C.P. West, G. Hernandez-Ramirez, E.E. Gbur, and T.B. Parkin. 2009. Nitrous oxide emissions from a bermudagrass pasture: Interseeded winter rye and poultry litter. *Soil Biology & Biochemistry* 41:1417–1424.

Schnabel, R.R., A.J. Franzluebbers, W.L Stout, M.A. Sanderson, and J.A. Stuedemann. 2001. The effects of pasture management practices. In *The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect,* edited by R.F. Follett, J.M. Kimble, and R. Lal. CRC Press.

Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tockoz, D. Hayes, and T.H. Yu. 2008. Use of US croplands for biofuels increases greenhouse gases through emissions from land use change. *Science* 319:1235–1238.

Short, S. 2001. Characteristics and production costs of U.S. cow-calf operations. Statistical bulletin 974-3. Washington, DC: U.S. Department of Agriculture, Resource Economics Division.

Singer, J.W., and K.J. Moore. 2003. Nitrogen removal by orchardgrass and smooth bromegrass and residual soil nitrate. *Crop Science* 43:1420–1426.

Singh, J., S. Saggar, D. Giltrap, and N. Bolan. 2008. Decomposition of dicyandiamide (DCD) in three contrasting soils and its effect on nitrous oxide emission, soil respiratory activity and microbial biomass: An incubation study. *Australian Journal of Soil Research* 46:517–525.

Six, J., S.M. Ogle, F.J. Breidt, R.T. Conant, A.R. Mosier, and K. Paustian. 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. *Global Change Biology* 10:155–160.

Sleugh, B., K.J. Moore, J.R. George, and E.C. Brummer. 2000. Binary legume–grass mixtures improve forage yield, quality, and seasonal distribution. *Agronomy Journal* 92:24–29.

Steinfeld H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales, and C. de Haan. 2006. Livestock's long shadow: Environmental issues and options. Rome: United Nations Food and Agriculture Organization.

Stout, W.L., and G.A. Jung. 1992. Influences of soil environment on biomass and nitrogen accumulation rates of orchardgrass. *Agronomy Journal* 84:1011–1019.

Traxler G., A.K.A. Acquaye, K. Frey, and A.T. Thro. 2005. Public sector plant breeding resources in the US: Study results for the year 2001. Washington, DC: U.S. Department of Agriculture, National Institute for Food and Agriculture. Online at *http://www.csrees.usda.gov/nea/plants/pdfs/plant_report.pdf.* Data tables at *http://www.csrees.usda.gov/nea/plants/pdfs/plant_tables.pdf*.

U.S. Department of Agriculture, Economic Research Service (USDA ERS). 2010a. Fertilizer use and price, Table 10. Washington, DC. Online at *http://www.ers.usda.gov/Data/FertilizerUse/.*

USDA ERS. 2010b. New feed grains data: Yearbook tables. Corn, sorghum, barley, and oats—Planted acreage, harvested acreage, production, yield, and farm price. Washington, DC. Online at *http://www.ers.usda.gov/data/feedgrains/Table.asp?t=01*.

USDA ERS. 2010c. U.S. beef and cattle industry: Background statistics and information. Washington, DC. Online at *http://www.ers.usda.gov/news/BSECoverage.htm.*

U.S. Department of Agriculture, National Agricultural Statistics Service (USDA NASS). 2010. National statistics for corn. Washington, DC. Online at *http://www.nass.usda.gov/Statistics_by_Subject/result.php?4FD1BD14-3251-3C45-8F15-0A16F4740261&sector=CROPS&group=FIELD%20 CROPS&comm=CORN.*

USDA NASS. No date. Commodity data. Washington, DC: U.S. Department of Agriculture. Online at *http://www.nass.usda.gov/Statistics_by_Subject/index.php?sector=CROPS.*

Vitousek P.M., R. Naylor, T. Crews, M.B. David, L.E. Drinkwater, E. Holland, P.J. Johnes, J. Katzenberger, L.A. Martinelli, P.A. Matson, G. Nziguheba, D. Ojima, C.A. Palm, G.P. Robertson, P.A. Sanchez, A.R. Townsend, and F.S. Zhang. 2009. Nutrient imbalances in agricultural development. *Science* 324:1519–1520.

Wachendorf, C., F. Taube, and M. Wachendorf. 2005. Nitrogen leaching from ^{15}N labelled cow urine and dung applied to grassland on a sandy soil. *Nutrient Cycling in Agroecosystems* 73(1):89–100.

Waghorn, G.C., and D.A. Clark. 2004. Feeding value of pastures for ruminants. *New Zealand Veterinary Journal* 52(6):320–331.

Waghorn, G.C., G.B. Douglas, J.H. Niezen, W.C. McNabb, and A.G. Foote. 1998. Forages with condensed tannins: Their management and nutritive value for ruminants. *Proceedings of the New Zealand Grasslands Association* 60:89–98.

West, T.O., and W.M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. *Soil Science Society of America Journal* 66:1930–1946.

Wilkins, P.W., and M.O. Humphreys. 2003. Progress in breeding perennial forage grasses for temperate agriculture. *Journal of Agricultural Science* 140:129–150.

Woodward, S.L., G.C. Waghorn, and P.G. Laboyrie. 2004. Condensed tannins in birdsfoot trefoil (*Lotus corniculatus*) reduce methane emissions from dairy cows. *Proceedings of the New Zealand Society of Animal Production* 64:160–164.

Young, A.W., and R.G. Kauffman. 1978. Evaluation of beef from steers fed grain, corn silage or haylage-corn silage diets. *Journal of Animal Science* 46:41–47.

Zemenchik, R.A., and K.A. Albrecht. 2002. Nitrogen use efficiency and apparent nitrogen recovery of kentucky bluegrass, smooth bromegrass, and orchardgrass. *Agronomy Journal* 94:421–428.

RAISING THE STEAKS

Global Warming and Pasture-Raised Beef Production in the United States

Beef production accounts for more global warming emissions in the United States than other foods, and contributes to other environmental problems including water and air pollution. In *Raising the Steaks*, the Union of Concerned Scientists evaluates the potential for pasture beef producers—a growing segment of the industry—to curb beef's environmental impact by adopting better management practices.

For example, our analysis shows that improving the nutritional quality of forage crops could reduce emissions of methane—a global warming gas 23 times more potent than carbon dioxide—by about 15 to 30 percent. Overall, better management practices on pasture (including those that increase soil carbon storage) could offset up to about 2 percent of annual U.S. heat-trapping emissions. And climate-friendly pasture practices can also reduce problems such as erosion and the pollution of streams and groundwater with nitrogen runoff.

Raising the Steaks also suggests how the farm bill and other federal policies can play a substantial role in reducing the climate change impact of pasture beef production. Incentives and technical support should be offered to help beef producers adopt the best management practices currently available, and federal research should be expanded to further develop climate-friendly practices.

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Citizens and Scientists for Environmental Solutions

The Union of Concerned Scientists is the leading science-based nonprofit working for a healthy environment and a safer world. This report is available on the UCS website at *www.ucsusa.org/raisingthesteaks*.

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