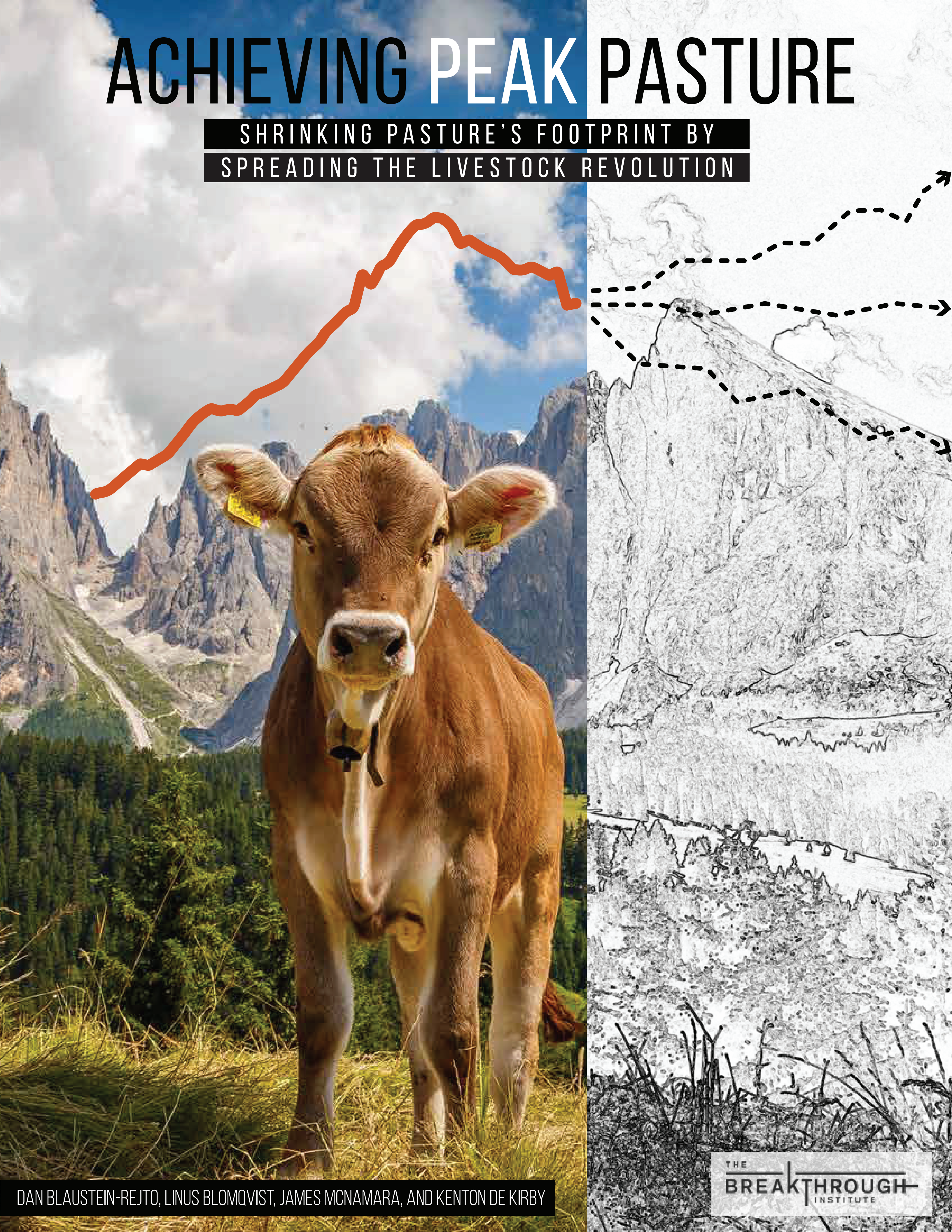

ACHIEVING PEAK PASTURE

SHRINKING PASTURE'S FOOTPRINT BY SPREADING THE LIVESTOCK REVOLUTION

DAN BLAUSTEIN-REJTO, LINUS BLOMQVIST, JAMES MCNAMARA, AND KENTON DE KIRBY

THE BREAKTHROUGH INSTITUTE

EXECUTIVE SUMMARY

Pastureland is by far the single largest human land use on the planet. Globally, we use twice as much land for producing meat and milk from cattle and other ruminants as we do for growing crops.

For centuries, global pasture area expanded, with severe environmental consequences. Since the 1700s, an area nearly the size of North America has been converted to pasture. Further, pasture expansion has been a major driver of deforestation in the Amazon and degradation of many of the world's natural grasslands, threatening biodiversity and worsening climate change.

In the past 20 years, however, something remarkable has occurred, something that few predicted: global pasture has begun to decline. According to data from the Food and Agriculture Organization of the United Nations, there are 140 million fewer hectares of pasture today than there were in 2000, an area roughly the size of Peru.

Many high-income countries saw pasture area peak as early as the 1960s and decline consistently since then. But in the past two decades, this pattern has spread to most of the rest of the world, with more than two-thirds of all countries now experiencing flat or declining pasture area. Notably, since 2000, pasture has also leveled off in the rapidly developing middle-income countries that saw the greatest pasture expansion in the late 20th century, including China and Brazil, as well as in low-income countries.

Driving this global trend is increasing productivity — producing more ruminant meat and milk with less land. Between 2000 and 2013, even as pasture area has declined, ruminant meat and milk production has gone up by 13% and 32%, respectively. In other words, there has been a great decoupling of production from pastureland — a "livestock revolution."

While some of this productivity growth is the result of raising more animals on the same amount of pasture (that is, higher stocking density), each animal is also producing more milk and meat. Both stocking densities and animal yields have improved across most of the world, except in sub-Saharan Africa (SSA), where animal yields have improved little, if at all, and stocking densities are reaching unsustainable levels.

Pasture's decline could be a boon for the environment, especially if it continues, but the future is by no means certain. One factor in particular threatens to reverse pasture's contraction. Rapid population and economic growth in parts of the developing world, especially SSA, in combination with persistently low animal yields, could herald a major expansion of pasture. Although economic development will probably drive productivity improvements along with demand, it is likely that SSA will experience a period of substantial pasture expansion as long as yields fail to keep pace with demand, following the pattern of other developing regions.

To a great extent, then, the future of global pasture — whether it continues contracting or expands once again — hinges on whether the livestock revolution comes to the developing world, and to SSA in particular.

Addressing the problem from the demand side by reducing food waste and meat consumption has clear potential. But given how much demand is projected to increase, especially in the developing world, demand-side efforts will not be sufficient to keep pasture growth at bay. The good news is that productivity could be improved substantially — enough to offset increases in demand. Many developing regions today operate well below their technical potential, and there are plentiful examples of countries vastly increasing their productivity over short periods of time.

As it has elsewhere, increasing productivity in the developing world will require intensification — more inputs, more intensive management, and in many cases, larger-scale operations.

Of course, while increasing productivity is an important objective for reducing land-use change, it is one of many possible social, economic, cultural, and environmental goals, and intensification efforts should respect the integral role of livestock in the lives, livelihoods, and cultures of local communities.

There are three primary levers for raising productivity: better feed, optimized breeds, and improved animal health. Ensuring that animals receive an energy-rich and nutritionally balanced diet is essential for improving animal yields, and higher productivity of forage grasses as well as supplemental crop-based feeds means that more feed can be grown on less land. Cattle can also be bred to be higher-yielding and better adapted to regional conditions. Finally, protecting animals' health and welfare makes them more productive.

Spreading the livestock revolution entails systemic change to regions' production systems and requires overcoming barriers to the adoption of new practices. And due in part to the possibility of rebound effects, the environmental benefits of intensification at local levels are not guaranteed. Targeted efforts by the public and private sector are therefore needed to both incentivize intensification and fulfill its environmental potential.

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INTRODUCTION: THE PASTURE PROBLEM

The pasture problem is one of the most significant challenges the world faces for conserving biodiversity and mitigating climate change. "Pasture" refers to land used to graze livestock (primarily ruminants such as cows, buffalo, sheep, and goats) to produce meat, dairy, and other products — and it is by far the single largest human land use on the planet.[1] Globally, we use approximately twice as much land for grazing animals as we do for growing crops.[2]

The picture becomes even more startling when one considers that the footprint of ruminants goes far beyond the pastureland on which they are grazed. Nearly one-fifth of global cropland area is used to grow feed for ruminants.[3] As a rough estimate, all the land that ruminants require — both pasture and cropland — amounts to a startling 47% of the Earth's agricultural land area.[3]

The dominance of ruminants is rivaled by their centrality to our current food and economic system. Ruminants account for almost 50% of animal protein produced globally.[3] They are equally important economically: the livestock sector employs roughly 1.3 billion people globally and accounts for 20% of agricultural GDP in the developing world.[4]

For centuries, global pasture area has expanded, leading to severe environmental consequences. Since the 1700s, an area nearly the size of North America has been converted to pasture.[2] Pasture expansion has been a major driver of deforestation in the Amazon and degradation of many of the world's natural grasslands. It is also threatening biodiversity and worsening climate change by releasing carbon stored in soils and plants and reducing future carbon sequestration.[5]

In 2016, there were approximately 156 million hectares more pastureland than there were in 1961, an area roughly the size of Mongolia.[6] This expansion of pasture has been driven by rising global demand for ruminant products, thanks to growing wealth and population size. By 2050, demand for beef alone is forecast to rise 61%

above 2012 levels, with the greatest growth occurring in developing countries.[7]

On the one hand, the growth of demand for ruminant products is a sign of human progress. It indicates that an expanding number of people can afford better, more diverse diets. On the other hand, growing demand could lead to substantial pasture expansion — as much as 400 million hectares according to one projection — if current trends continue.[8] This is the pasture problem: the need to meet rising demand while preventing, or even reversing, the expansion of pastureland to arrest continued degradation of natural habitats and excessive release of carbon.

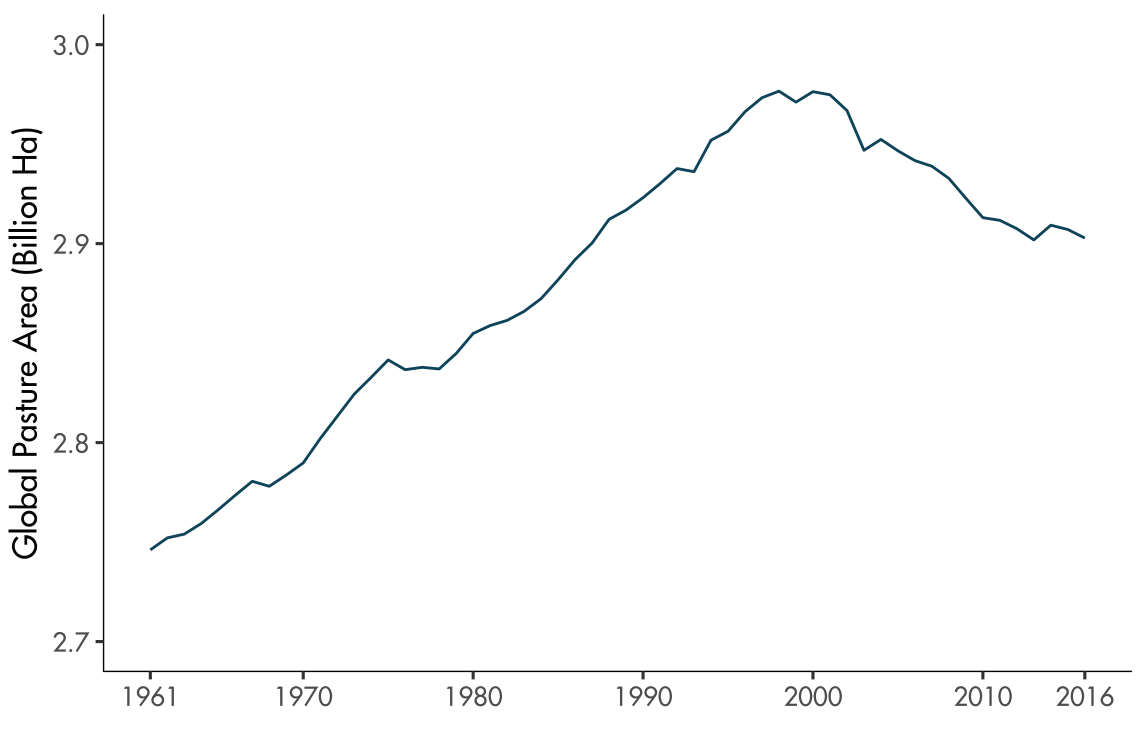
Efforts to reduce consumption and food waste are important and needed, but production-side improvements are likewise critical, and often undervalued, especially given the forecasted growth in demand for ruminant products. This report endeavors to present a clear and empowering vision for addressing the production side of the equation.

The first chapter examines global trends in pasture area over the past half century, with a focus on the surprising decline in pastureland during the past 20 years, a development that could point the way toward real and lasting environmental progress. This chapter documents how increasing productivity has been a key driver of pasture's decline and indicates that further productivity growth is vital for reducing agricultural land use. The following chapter then examines the key production levers for raising productivity: better feed, breeds, and animal health. And the final chapter constructs a framework for thinking about the role of public policy in bringing about the systemic changes that are needed to support broad improvements in pasture productivity.

PEAK PASTURE AND THE LIVESTOCK REVOLUTION

In the last 20 years, something remarkable has occurred. The Food and Agriculture Organization of the United Nations (FAO) reported that global pasture area has begun to decline after centuries of growth (Figure 1).[9] There were an estimated 74 million fewer hectares of pasture in 2016 (the most recent year of FAO data) than there were in 2000. This amounts to an area roughly the size of Chile and is equivalent to about one-third of the expansion that occurred between 1961, when FAO records begin, and 2000.

Figure 1: Global Pasture Area Has Been Declining Since 2000



Source: FAO (2019).

Despite some legitimate concerns about the accuracy of the FAO data[10], the contraction of global pasture is corroborated by other models, including those that use a mixture of remote sensing data and national inventories such as the History Database of the Global Environment (HYDE) (Figure A1).[11]

Similarly, data-quality issues for individual countries do not negate the larger downward trend. For instance, Australia began reporting pasture area differently in 2015, making it appear as though its rate of pasture decline sped up to about 20 times the 30-year average. However, all the primary results in this report correct for this, assuming that the earlier rate of decline in Australia remained constant. All results presented here also omit Saudi Arabia, as a previous FAO report has done, given the inflated values the country reports to FAO.[12] This and other data adjustments, omissions, and corrections are explained in Appendix 2.

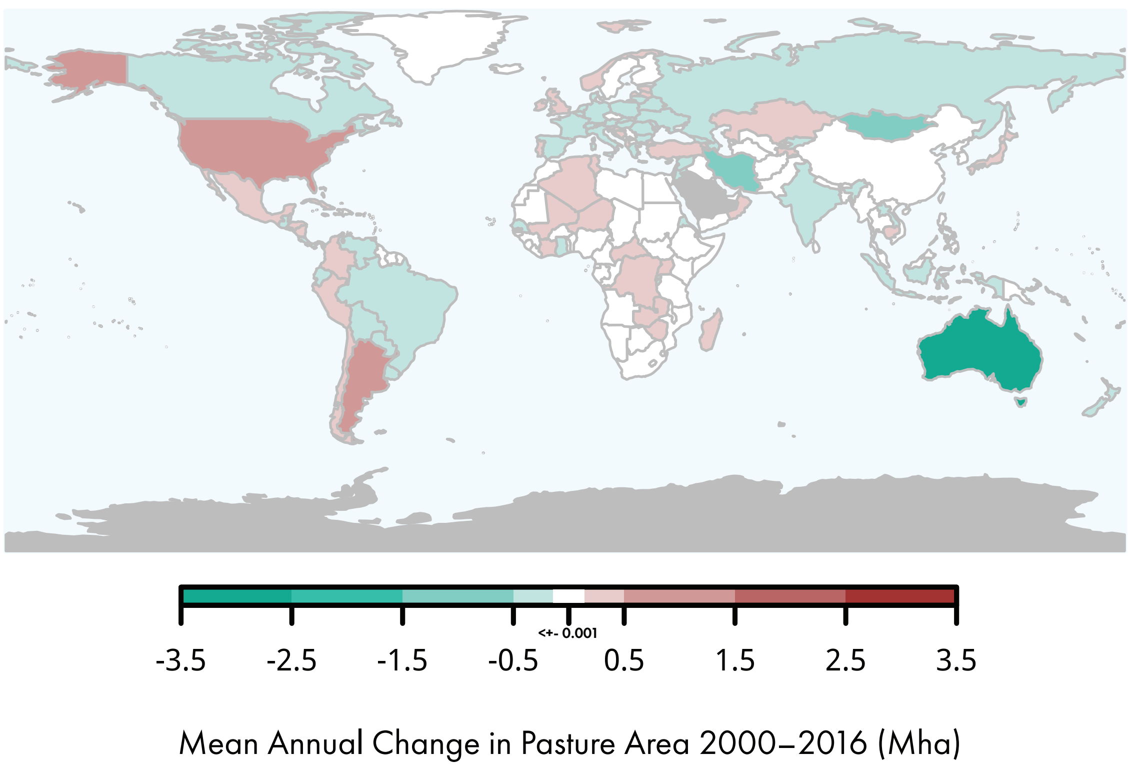
Today, ruminant production depends not only on grazing land, but also on cropland for growing animal feed, including cereals such as maize, sorghum, and millet; legumes such as soy and alfalfa; and oilseeds such as sunflower and canola. Although cropland for cattle feed has increased by less than 25 million hectares (Mha), this increase is still outweighed by the larger decline in pasture area.[3,13] The result is that total agricultural land devoted to producing meat and milk from ruminants has shrunk by approximately 50 Mha since 2000.

Peak Pasture Is a Worldwide Trend

Rather than reflecting anomalous trends in select countries, the recent contraction of global pasture area is a widespread phenomenon. Between 2000 and 2016, pasture area was flat or declining in two-thirds of countries (Figure 2). These include countries that have seen pasture area decline for decades as well as those that saw large pasture expansions in the 20th century and only recent declines. Today, as a result, pasture has declined or plateaued in nearly all major world regions.

In some countries, pasture area has steadily fallen for decades. Most of the long-term decline has occurred in high-income countries, which have seen an average contraction in pasture area of about 10% since 1961 (Figure 3). Both Europe and North America, which belong mostly to the high-income group of countries, have less pasture now than they did in 1961, as does Australia, which has experienced the single largest decline worldwide (Figure 4). In 67 countries (approximately one-third of countries), pasture area is now smaller than it was in 1961.

Figure 2: Pasture Area Has Been Flat or Declining in Two-Thirds of Countries in the 21st Century



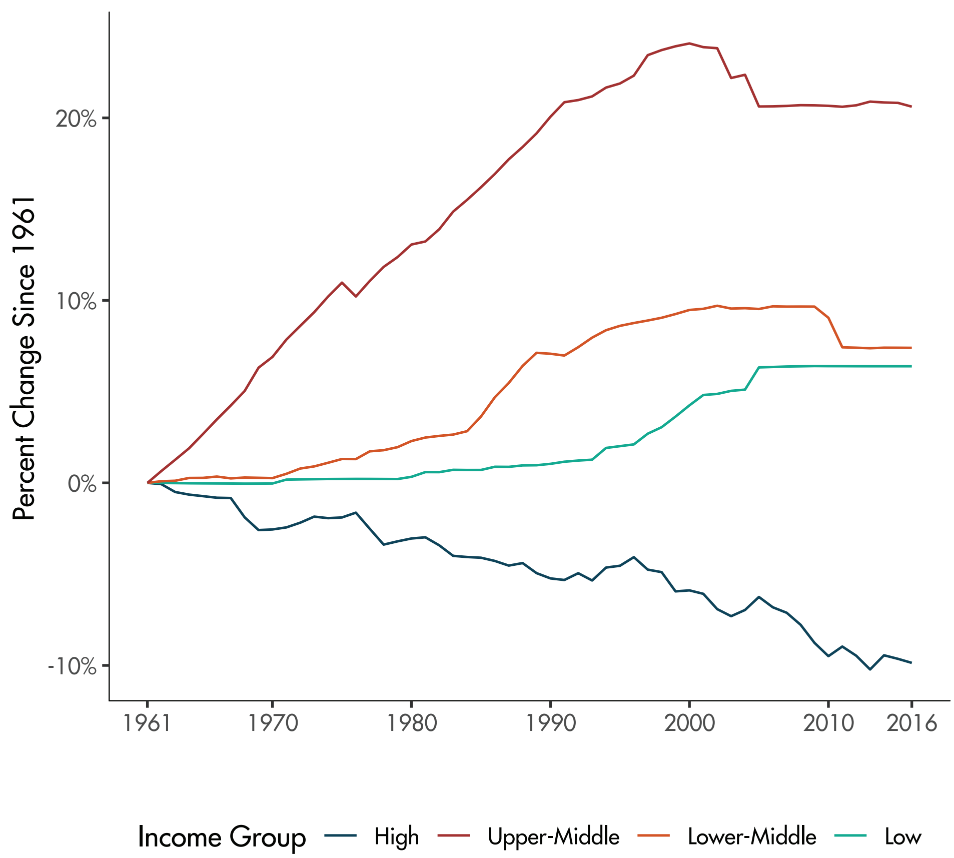
Omitted countries shaded gray.

In countries that saw large expansions in the 20th century (in particular, rapidly developing upper-middle-income countries with large populations and vast amounts of available land to clear), pasture area is also beginning to contract or plateau. For example, Brazil and China have seen their pasture area level off after growing rapidly in previous decades (Figure 4). Although China's reported pasture data do not appear highly robust (e.g., they didn't report official pasture area statistics to the FAO between 1994 and 2010[i]), other data sources such as estimates of grassland area[ii] or remotely sensed pasture seem to confirm that pasture area has in fact leveled off.[14]

i Personal communication, F. Tubiello, 2019.

ii *Ibid*.

Figure 3: Pastureland Growth Is Closely Tied to Economic Growth

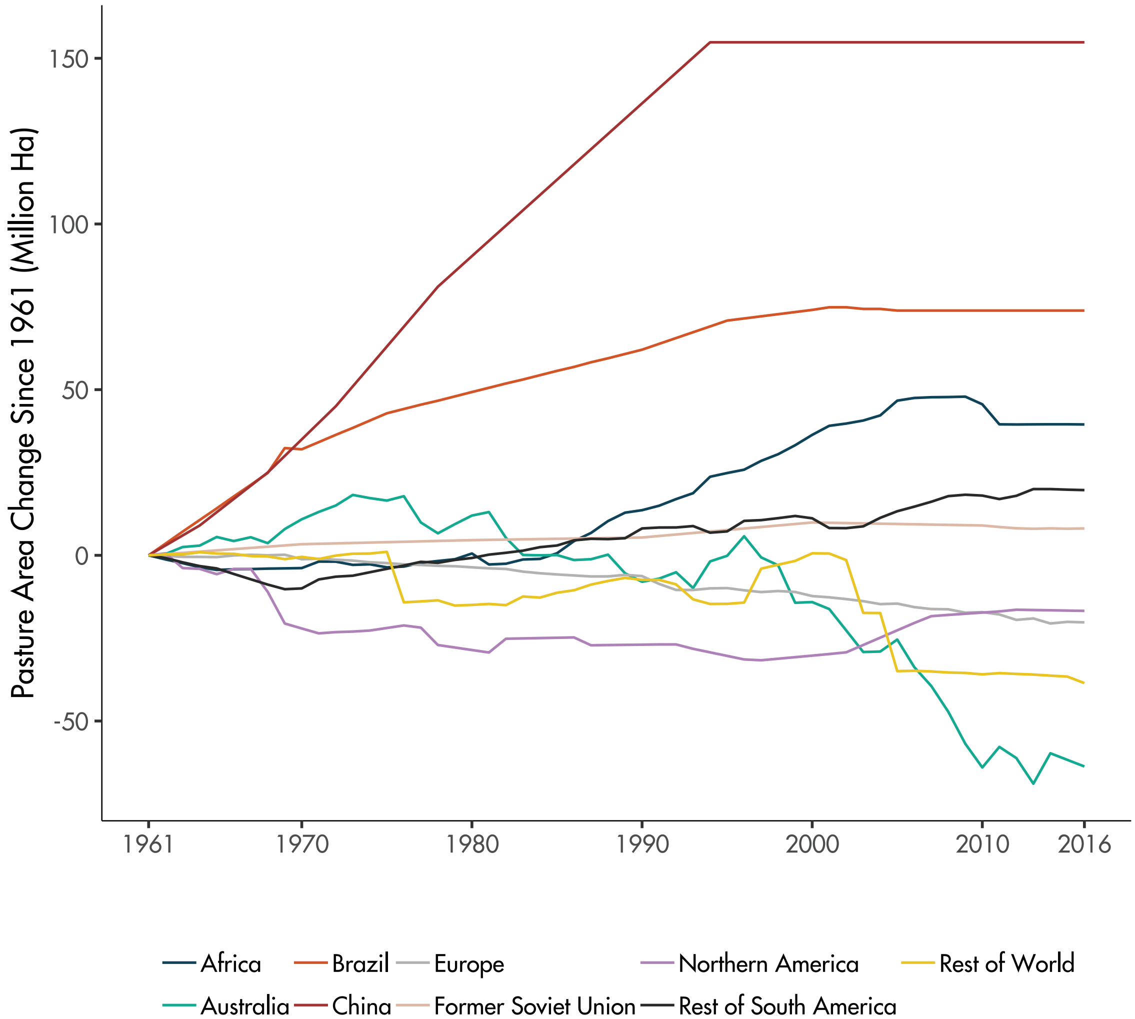


Omitting countries missing World Bank income group. Sources: FAO (2019), World Bank (2018).

Pasture area change has stalled or contracted in lower-middle and low-income countries as well. The lower-middle-income group saw pasture area peak around 2000, and the low-income countries, after seeing pasture area grow rapidly from around 1990 to 2005, have reported no substantial changes in pasture area in the most recent 10 years on record (2006–2016; Figure 3). Altogether, since 2000, pasture area has contracted in 29 (33%) of the countries that saw pasture growth during 1961–2000.

This widespread trend of declining or plateauing pasture area has more than offset the simultaneous pasture expansion in select regions. During 2006–2016, pasture area expanded most rapidly in the United States, Argentina, and Niger, yet the growth rate in these countries was a fraction of what China or Brazil saw in the 20th century and, again, not sufficient to offset large declines elsewhere (Figure A2).

Figure 4: Pasture Area Is Declining or Flat in Nearly All Regions Since 1961



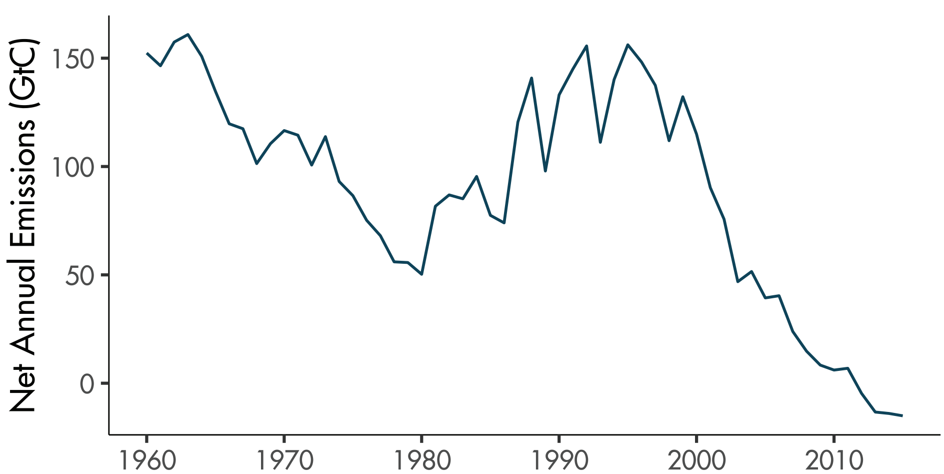
Source: FAO (2019).

Peak Pasture Holds Positive Environmental Potential

The shrinking footprint of global pastureland has the potential to mitigate climate change and safeguard biodiversity. Reforestation of former pasture area, as well as avoiding deforestation in the first place, increases soil and aboveground carbon stocks. Although carbon sequestration rates are highly variable and depend on a wide range of local agroecological conditions, recent assessments have estimated that reforestation in temperate and tropical climates typically increases sequestration by 2.8 and 4.7 tons of carbon per hectare per year, respectively. These rates are significantly greater than typical sequestration rates associated with "natural climate solutions" for improving pasture, such as an estimated rate of around 0.6 tons per hectare per year by planting legumes.[15]

Indeed, although some former pastureland has been converted to cropland or urban uses, there are indications that substantial land has been reforested or otherwise restored in environmentally beneficial ways. For example, according to FAO records, between 1990 and 2015, the area of forest in Europe (a region that has experienced some of the most significant declines in pasture) has increased by about 12 million hectares, nearly 8%. Such restoration, combined with a slowdown in deforestation, has cut GHG emissions from land-use change associated with pasture. One model estimates that abandonment of pasture is now sequestering more carbon than is lost from converting forest to pasture (Figure 5).[16]

Figure 5: Emissions from Conversion Between Forest and Pasture Have Fallen



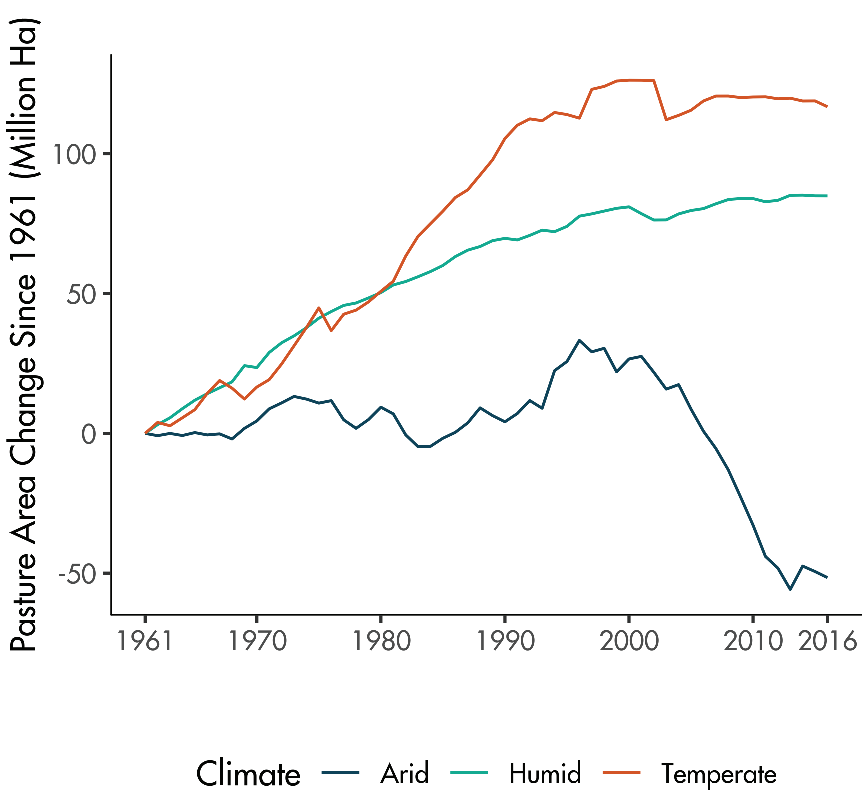
Source: Houghton & Nassikas (2017).

Even restoration of marginal and arid lands has benefited biodiversity. Although limited levels of grazing can be compatible with wildlife in some landscapes, reductions in pasture area have resulted in important conservation successes. In the steppes of Kazakhstan, the endangered saiga antelope has benefited. And in Iran, another country that has experienced significant contractions in pasture, the Asiatic cheetah (one of the world's most elusive and endangered big cats) is showing signs it could be coming back from the brink of extinction as conflict with nomadic herders eases owing to the contraction of extensive grazing lands.[17]

However, the environmental benefits of pasture contraction vary widely by biome, region, and climatic zone. While contraction appears to have led to a net carbon sequestration, it could still have a negative impact on wildlife and biodiversity if it results from a large contraction in arid regions and a comparatively smaller expansion in tropical areas.

Unfortunately, this scenario may be the reality (Figure 6)[18], which underscores the importance of accelerating the factors driving the reduction in pasture area — particularly in tropical regions.

Figure 6: Humid and Temperate Regions Comprise an Increasing Share of Global Pasture Area

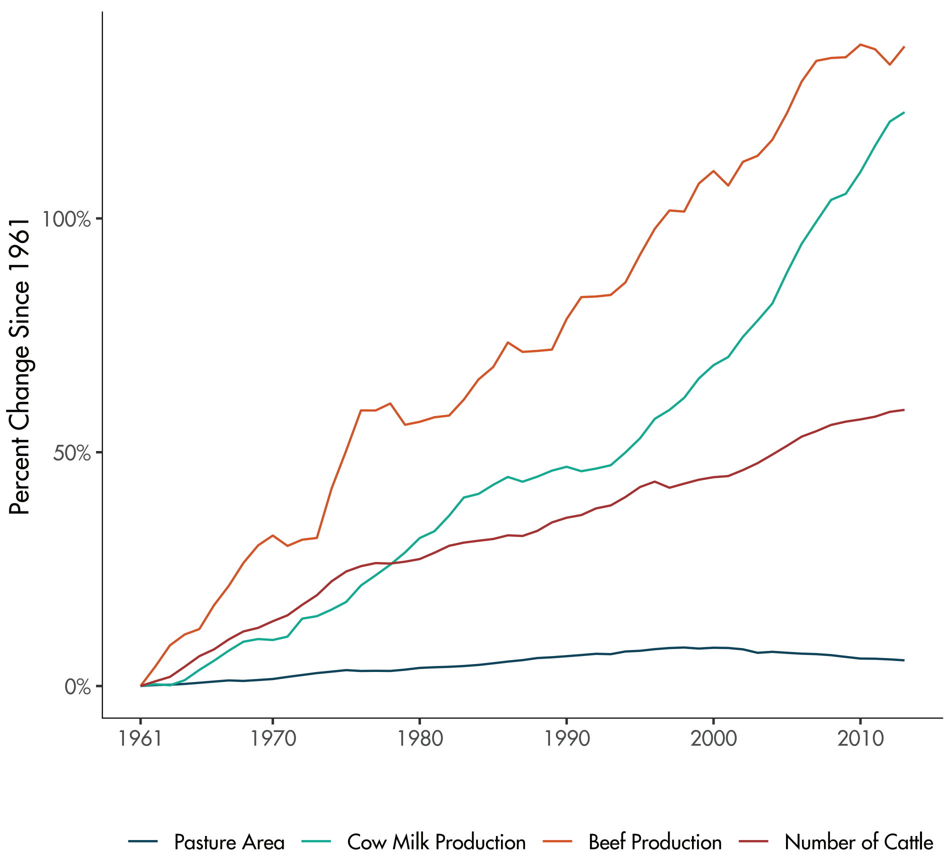


Source: Adapted from Godde et al. (2018).

Productivity Gains Are Key to Peak Pasture

What is perhaps most remarkable about the decline in global pasture is that it is occurring against a backdrop of continued increases in production. Between 2000 and 2013, production of beef and cow milk rose by 12% and 31%, respectively (Figure 7). In other words, it appears that production is becoming *decoupled* from pastureland, and thus no longer requires increases in pasture area.

Figure 7: Production Continues Decoupling from Pasture Area



Omitting Former Soviet Union. Source: FAO (2019).

This decoupling has been driven by increases in a variety of productivity measures (see box below), which have reduced the pressure to convert native vegetation to grazing land.

MEASURING PRODUCTIVITY

"Overall productivity" refers to the amount of beef or dairy produced per hectare of land per year. Overall productivity can be decomposed into several different sets of metrics. One set defines productivity in terms of the characteristics of animal feed: how much is available, how much is eaten, and how efficiently animals turn it into meat or dairy. Another set does so in terms of animal characteristics: how many animals are raised on a given amount of land and how much product comes from each animal. Overall productivity can be estimated by multiplying the metrics in each set by one another.

Overall Productivity Breakdown #1: Feed Characteristics

Forage yield — total biomass of animal feed produced per hectare per year
Utilization rate — proportion of forage consumed by animals
Feed efficiency —animal production (in protein, calories, kg, or another unit) per unit of feed

Overall Productivity Breakdown #2: Herd and Animal Characteristics

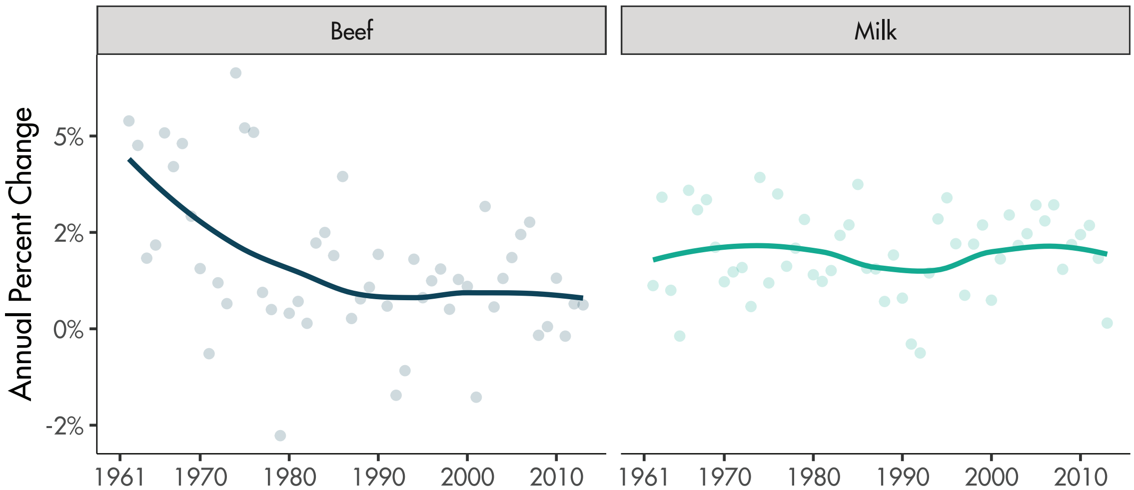
Stocking rate — number of animals per hectare of grazing land
Animal yield — production per animal per year

In some circumstances, data on only some of the above metrics are available. Globally, the FAO documents only animal yield, for instance.

For most of the period since 1961, demand for beef, milk, and other ruminant products grew faster than productivity, driving an expansion of pasture area. This expansion was determined primarily by population growth, followed by shifts in eating habits among people in developing countries, who began eating higher-quality diets with a greater share of animal products. From 1961 to 1994, global population growth drove an estimated 66% of the expansion of agricultural land for livestock and dietary changes accounted for the remainder.[13]

Throughout this period, however, productivity increased steadily in most of the world while population growth and demand for some ruminant products, such as beef, both slowed (Figure 8).[19] Around 2000, overall productivity growth edged ahead of demand growth, enabling pasture area to fall. The contraction of pasture area starting in 2000, therefore, did not reflect any particular event; rather, it was the outcome of a steady process of rising productivity and slowing demand.

Figure 8: Since 1961, Global Demand for Beef Has Slowed While Demand for Dairy Has Remained Steady



Categories represent FAO 'Bovine Meat' and 'Milk - Excluding Butter' items.
Lines derived from LOESS smoothing. Source: FAO (2019).

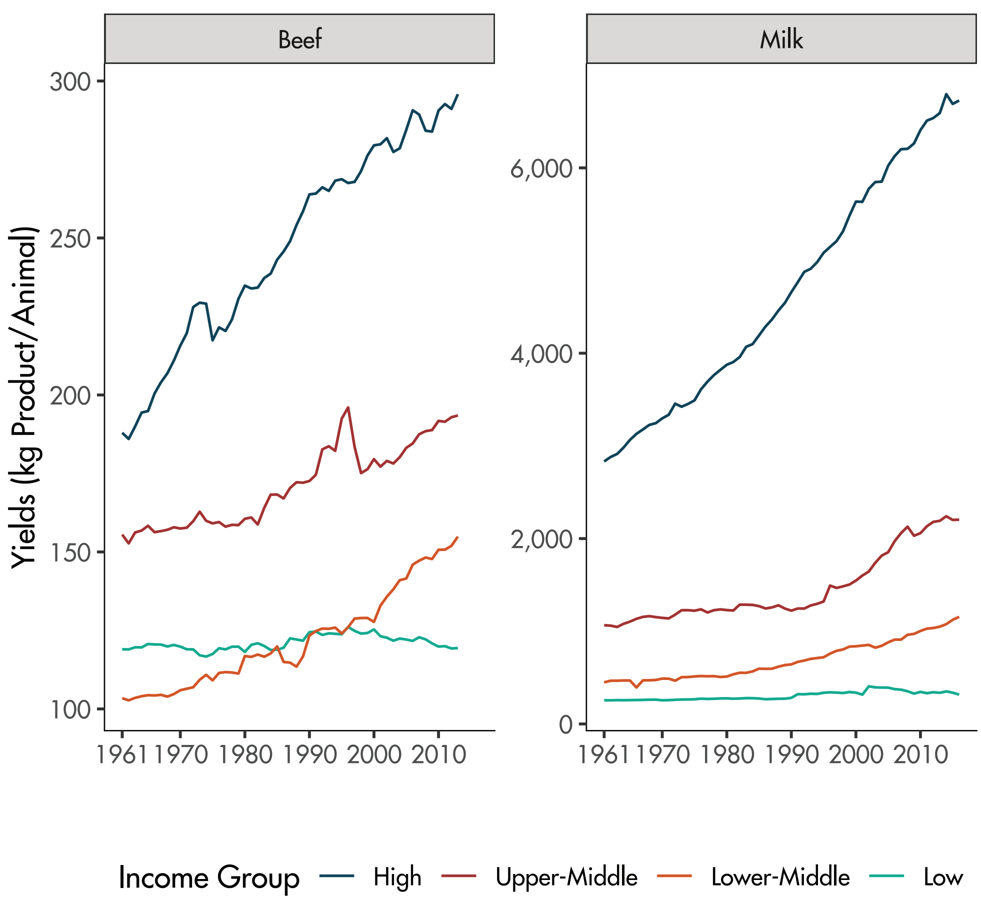
The upward march of productivity can be considered a "livestock revolution," similar in some respects to the dramatic increases in crop productivity that arose from the Green Revolution. For decades, population growth, urbanization, and income growth, particularly in developing countries, has spurred a large global increase in animal-sourced foods.[20] In turn, livestock producers have been shifting from extensive production systems in which grazing occurs on unmanaged natural grasslands to more-intensive production systems that manage pasture to increase grass yields and incorporate energy-rich feeds such as cereal crops.[20] As a result, animal yields and feed efficiency have increased almost everywhere. The cattle industry, the most dominant user of pasture globally, saw meat and milk yields grow 29% and 22% since 1961.[iii]

These measures of productivity are generally highest, and have increased the most, in higher-income countries (Figure 9 and Figure 10). For instance, beef yields in Africa, Brazil, and China are all substantially lower than in higher-income Australia — 40%, 12%, and 46% less, respectively. Similarly, feed efficiency in the higher-income regions of Western Europe, North America, and Oceania has historically been greater than in other regions, contributing to the large-scale pasture contraction.

iii Omitting production data for countries that were part of the former Soviet Union.

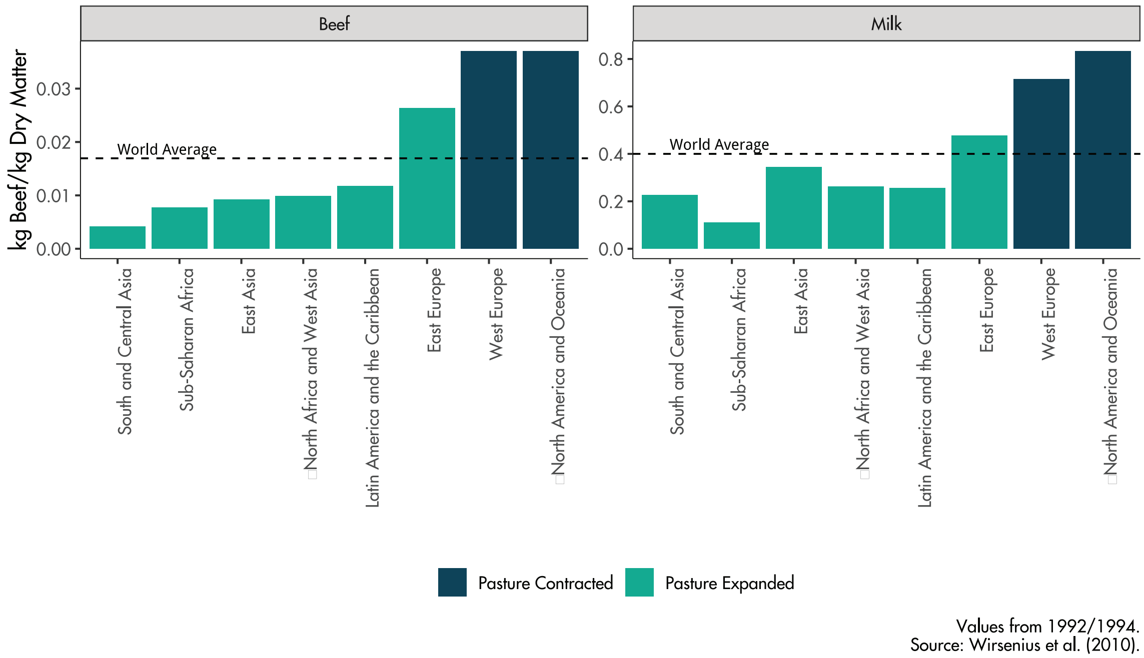
That wealthier countries perform better on these productivity metrics is hardly surprising. While animal productivity is inherently shaped by climate and geography (e.g., arid regions have lower productivity than temperate ones), it is also driven largely by the production system and the intensity of production[21] — factors closely related to economic development. For example, producers in developed countries typically give cattle more crop-based feeds, including high-energy grains, than those in developing countries.[21] As countries urbanize, industrialize, and strengthen government institutions, governments and the private sector tend to invest in the infrastructure, technologies, and programs that help producers adopt crop-based feeds and other productivity-enhancing practices.[12]

Figure 9: Animal Yields Have Increased Most in High-Income Countries



Omitting Former Soviet Union & countries missing World Bank income group.
Sources: FAO (2019), World Bank (2018).

Figure 10: Feed Efficiency is Highest in High-Income Regions



Stocking rates also appear to have increased, though with more ambiguous effects on productivity and sustainability. While reliable global statistics of stocking rates are not available, FAO data can be used to calculate the number of animals per hectare of pasture, a rough proxy (Figure A3).[iv] Globally, the number of cattle stocks per hectare increased 57% from 1961 to 2016. While this shift is partially the result of changes in the mix of animals grazing,[v] it also indicates an increase in stocking rates.

Increased stocking rates raise production per unit of pasture in the short term, but high rates are not necessarily sustainable. They can lead to overgrazing, which damages the soil, reduces forage production, and therefore diminishes overall productivity.[22] Overgrazing raises concerns for regions, such as sub-Saharan Africa (SSA), where demand for ruminant products continues to increase while animal yields have stagnated and stocks have increased (Figure A3). Researchers estimate that approximately 48% of grassland area used for agriculture in SSA is degraded.[23] Further de-

iv FAO values for "stocks," which is the number of animals of a species in a country at a single point in time, divided by area of "land under perm. meadows or pastures."

v For example, if a country shifts from 100,000 cattle and 100,000 sheep to 0 cattle and 200,000 sheep while keeping pasture area constant, the stocks of sheep per total hectares of pasture will double, but the actual stocking rate will not have increased if the sheep are spread out over the pasture that the cattle used to graze.

mand increases cannot be met through greater stocking rates alone: either pasture area must expand or other productivity metrics must improve.

Putting aside ambiguous productivity gains from higher stocking rates, improvements in animal yields, feed efficiency, and other productivity metrics have spared vast amounts of forest and other land from being converted to grazing. In 2013, approximately 142% more cattle meat and 141% more cattle milk were produced for each hectare of pasture than in 1961. If the efficiency of the global cattle system were the same in 2016 as it was in 1961, more than 4 billion additional hectares of pasture — an area of land larger than China, the US, and Canada combined — would be required to support the same level of production.[vi]

But are recent rates of growth in animal yields and other forms of livestock productivity sufficient to keep pasture expansion at bay? Or will population growth, more meat-heavy diets, or even a slowdown in productivity cause the recent peak in pasture to reverse?

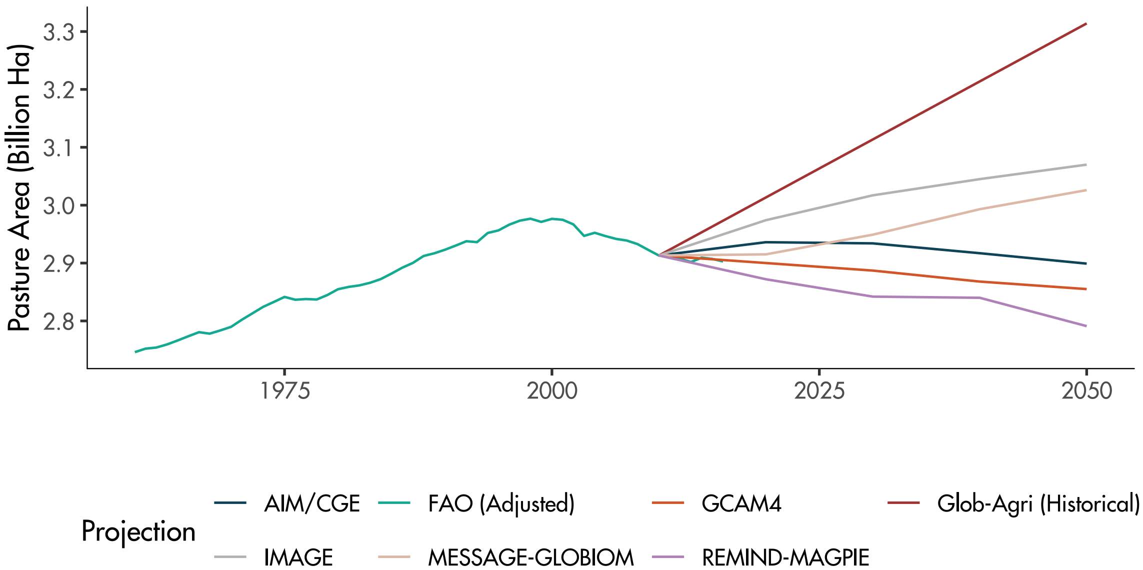
Risk Factors for Pasture Re-Expansion

If recent trends continue, with productivity keeping pace with or increasing faster than demand in virtually every region of the world, we may see global pasture area decline further. This would upend many projections that foresee pasture area increasing at least until 2050 (Figure 11). To illustrate, the MESSAGE-GLOBIOM model, which the global climate modeling community has chosen to represent a "middle-of-the-road" scenario, projects pasture expansion of 113 Mha from 2010 to 2050.[vii,24] In addition, the GlobAgri-WRR model developed by the World Resources Institute projects pasture expansion of 401 Mha from 2010 to 2050 if crop and livestock productivity increases at roughly the same rate as it has historically.[8] Notably, these projections are consistent with pasture area trends from 1961–2000 but do not account for the post-2000 decline. In fact, most scenarios predicting increases in pasture assume a sharp turnaround from the trend of the past 20 years. As of 2016 — just six years after these forecasts' base year of 2010 — the forecasts have already diverged from real-world data trends by tens of millions of hectares. In other words, the trends of the past two decades would need to change significantly for these forecasts to come true.

vi Assuming, for simplicity of calculation, that all pasture was devoted to cattle production.

vii Under the Shared Socioeconomic Pathway 2 (SSP2) baseline.

Figure 11: Most Analyses Project Pasture Expansion Through 2050 Under Business-as-Usual Scenarios



FAO historical pasture data (adjusted) shown in turquoise.
Sources: Riahi et al. (2017), Searchinger et al. (2018).

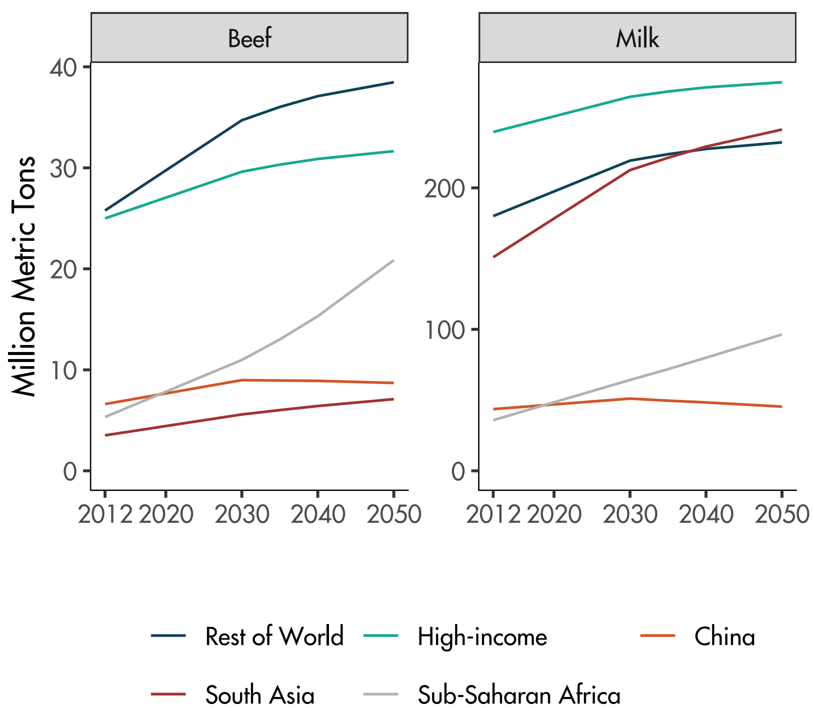
Nevertheless, the recent decline in pastureland is far from guaranteed to continue. One notable factor that may cause the trends of the past two decades to reverse is rapid demand growth combined with slow productivity growth in low-income regions, especially SSA.

Demand Outpacing Productivity in Low-Income Regions

At some point in their history, most regions have gone through an expansionary phase, when demand is growing faster than productivity, leading to a rise in pasture area. Countries that have long been considered high-income likely finished that phase before the FAO records began, and many have seen declines in pasture area since then. By contracst, many countries that experienced substantial economic development in recent decades went through their expansionary phase in the decades leading up to 2000 but have since largely stabilized. However, some low-income regions, SSA in particular, have yet to undergo an expansionary phase and now seem on the precipice of one. Although economic development will probably drive productivity improvements as demand increases, SSA is nevertheless expected to follow the pattern of other developing regions and first experience large pasture expansion as productivity fails to keep up with demand growth. The MESSAGE-GLOBIOM model,[viii] for instance, projects pasture area to expand by 73 million hectares in the Middle East and Africa between 2010 and 2050 — more than in any other region.[24]

As of 2017, the United Nations projected that population will grow in Africa by 1.3 billion people by 2050, accounting for 59% of global population growth.[25] Economic growth is also expected to rise, with GDP per capita in Nigeria, for example, projected to grow 50% faster than in the US or Australia.[26] These two trends could lead to rapid growth in the demand for beef and milk throughout the continent, with beef and milk consumption in SSA forecast to more than double 2012 levels by 2050 (Figure 12).

Figure 12: Forecast Demand for Ruminant Meat and Dairy Products

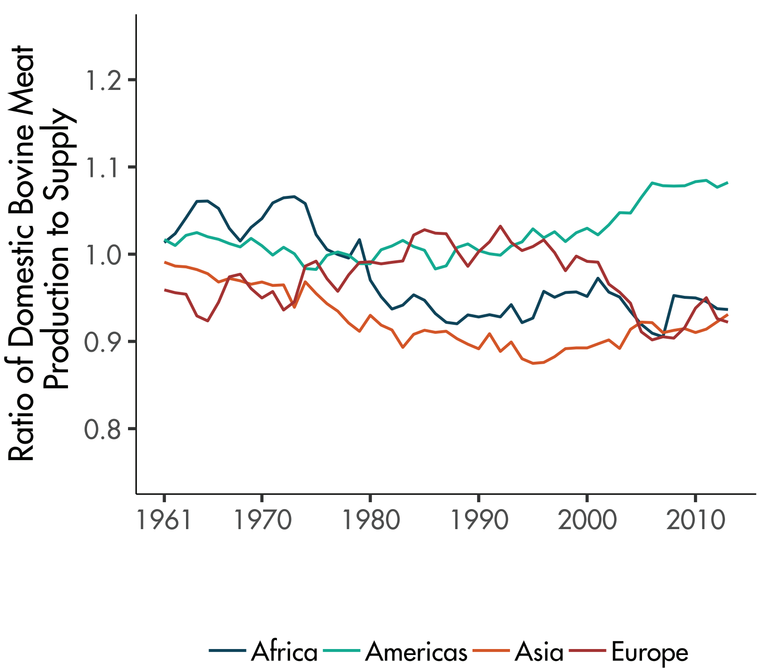


Values are for 'Beef and veal' and 'Raw milk' FAO items.
Source: FAO (2018).

viii Under the scenario "SSP2 baseline."

If SSA and other regions where demand is projected to rise continue to have low levels of productivity growth, their pasture area will likely expand. Many low-income countries, particularly those in SSA, not only have low absolute animal yields and feed efficiency, but also have seen little yield growth in recent decades (Figure 9, Figure 10, and Figure A3). The majority of ruminants in SSA are kept in arid and semi-arid zones where production potential is limited compared with more humid zones.[27] Combined with other factors (e.g., slow economic growth, poor infrastructure, and high animal disease pressure), poor grazing land contributes to cattle and other ruminants having low weights at maturity, high calf mortality rates, low fertility rates, and low meat and milk yields.[27] In addition, utilization rates (the proportion of seasonal forage eaten by animals) are low in SSA — only 10% compared with 16% in Latin America and higher values elsewhere.[28] Thus, unless productivity growth accelerates, SSA and other regions with rapidly growing demand may be in for a pasture boom. Whether this translates into a reversal in global pasture trends depends on the rate at which other regions' pasture area declines.

Figure 13: Domestic Production Nearly Equals Consumption in Every Region Since 1961



Omitting Oceania, which produces over 2x domestic supply.
Source: FAO (2019).

Further, international imports are unlikely to mitigate this pressure to expand pasture area. Rising demand in any given region is likely to be met with a corresponding increase in regional production. Even regions that import large amounts of ruminant meat or milk, such as Latin America, export almost equal quantities. In fact, for the past five decades, the ratio of production to consumption has been almost constant and broadly equal to one in every global region, with the exception of Oceania (Figure 13).

To a great extent, then, the future of global pasture — whether it continues contracting or expands once again — hinges on whether the productivity growth of the livestock revolution comes to the developing world, and to sub-Saharan Africa in particular.

SPREADING THE LIVESTOCK REVOLUTION: KEY LEVERS FOR INCREASING PRODUCTIVITY

In a world whose population is expected to reach nearly 10 billion by 2050,[ix] raising global livestock productivity will be vital to prevent pasture expansion, mitigate climate change, and preserve biodiversity.[25] According to the World Resources Institute, productivity of livestock and livestock feed will need to grow faster than it has historically in order to meet projected demand *without* converting additional native vegetation to agriculture. Improving productivity is especially important in regions where it remains low and where demand is expected to soar, such as sub-Saharan Africa (SSA).[8]

Addressing the problem from the demand side — by reducing food waste and meat consumption — clearly has potential. But given how much demand is projected to increase, especially in the developing world, demand-side efforts will not be enough.[8] Increasing productivity is essential and will require greater input use, more-intensive management, and in many cases larger-scale operations — hereafter referred to with the shorthand "intensification."

The good news is that intensification has enormous potential to meet rising demand while preventing pasture expansion, even reducing it further. While the Food and Agriculture Organization of the United Nations (FAO) projects that demand for ruminant meat and milk will rise dramatically (approximately 50% between 2010 and 2050), studies suggest that intensification could meet this demand by doubling or even tripling productivity on existing lands.[29,30] For instance, a 2014 study found that beef production per hectare in Brazil was only at one-third of its potential. Raising productivity to 70% of its potential would liberate 36 million hectares of pasture from production — about one-fifth of Brazil's current pasture area — allowing this land to be returned to nature.[31]

ix The 9.8 billion estimate reflects the "medium-variant" projection developed by the United Nations Department of Economic and Social Affairs.

Moreover, substantial productivity improvements are not just theoretically possible, but also practically attainable. A study of mixed crop-livestock production systems in East and West Africa found that meat and milk production on the best-performing sites was up to 167% higher than on lower-performing farms nearby.[32] In Colombia, adoption of some types of intensive pasture management increased cattle production per hectare up to fourfold.[33]

Of course, while increasing productivity is an important objective for reducing land-use change, it is one of many possible social, economic, cultural, and environmental goals, and intensification efforts should respect the integral role of livestock in the lives, livelihoods, and cultures of local communities.

> The good news is that intensification has enormous potential to meet rising demand while preventing pasture expansion, even reducing it further.

Broadly speaking, there are three levers for increasing productivity: (1) feeds, (2) breeds, and (3) animal health. Ensuring that animals receive an energy-rich and nutritionally balanced diet is essential for improving animal yields, and greater productivity of forages (grasses and other plants for grazing) and feed crops means more feed can be grown on less land. Additionally, cattle can be bred to be higher-yielding and better adapted to regional climates. Finally, protecting animals' health and welfare makes them more productive.

There is no one-size-fits-all pathway towards higher livestock productivity. Every region and animal operation will need to identify what practices are most suitable and effective for them. But raising productivity will invariably require pressing these levers.

Lever 1: Feeds

Animal feeds are a key determinant of livestock's land footprint. When feeds are higher-yielding (more produced per hectare) and higher-quality (more digestible and nutritious), less land is needed to produce a given amount of meat and milk. To appreciate the impact of feed quality on productivity, for example, consider that cattle in SSA require about *one order of magnitude* more feed per kilogram of beef produced than in Europe or North America, and thus substantially more land.[21]

Improved feed quality reduces not only land use but also greenhouse gas (GHG) emissions.[21] Ruminants with more nutritious diets gain more weight, reach slaughter weight quicker, and consume less feed per unit of meat or milk produced, thereby reducing methane emissions, a potent GHG generated through ruminants' digestive process. Better feeds also reduce the production of manure, another source of GHG emissions from animals. These impacts can lead to large differences between systems. Research indicates that ruminants in parts of East Africa produce 50–100 times more GHG emissions per unit of meat than in much of Europe, where feed efficiencies are higher.[21] It is not surprising, then, that improving feed quality was ranked by one study as among the most powerful ways of reducing GHG emissions from the livestock sector.[34]

There are three pathways to improving productivity through feeds: improving pasture management, following grazing best practices, and adopting crop-based feeds.

Pasture Management

A variety of approaches to managing pastureland, from cultivating specific grasses to fertilizing the land, can raise ruminant productivity by increasing the yields and nutritional quality of forages. One of the most effective ways of improving forage yields and quality is by planting fast-growing, nutritious grass species. For example, *Brachiaria* and *Cynodon spp.* provide substantial yield improvements over many native grasses in parts of Latin America. When fertilized, yields from monocultures of *Cynodon spp.* can reach an astounding 32 tons of dry matter per hectare per year.[35]

These improvements in forage yield can raise overall productivity as well as carbon sequestration. In the Brazilian Cerrado (a vast tropical savanna ecoregion), daily weight gain and milk production of animals grazed on *Brachiaria* pastures were three times higher than for animals grazed on native grasses. In addition, replacing native grasses with deep-rooted *Brachiaria* increases soil carbon sequestration — storing up to 4.5 tons of carbon dioxide-equivalent per hectare per year — and can improve animal nutrition enough to halve methane emissions per kilogram of meat.[22,36]

***Brachiaria* pasture in Brazil**

Fertilization is also important for maintaining and increasing forage yields and quality, especially in tropical soils, which are particularly prone to rapid degradation. Trials in the Brazilian Cerrado found that applying fertilizer more than doubled the yields of *Brachiaria*.[37] Growing protein-rich legumes such as lucerne (*Medicago sativa*, also known as alfalfa) or *Leucaena* provides additional nitrogen, reducing the need for fertilizers and improving the nutritive value of the feed. Further, animals in tropical environments fed on diets rich in such legumes produce less methane per unit of forage they consume (more than 20% less according to one meta-analysis) compared with diets based solely on grasses.[38]

Another option for improving productivity is to incorporate trees and shrubs into grazing land.[39] Although adopting such "silvopastoral" systems can be complex and slow to implement, requiring high up-front costs and specialized knowledge, it offers many benefits.[40] Shade from trees and shrubs helps reduce heat stress in animals, supports faster weight gain, reduces water loss from plants, maintains humidity, and lowers temperatures, thereby improving productivity. A ten-year study of six beef and dairy farms in Colombia showed large improvements in beef and dairy production under a silvopastoral grazing regime, with the amount of animals, beef production, and dairy production per hectare increasing in all cases up to several-fold.[33]

Silvopastoral systems also can improve biodiversity and carbon sequestration.[39] Their more diverse plant communities led, in one survey of farmers, to 71% of respondents reporting a dramatic increase in bird abundance, for example.[41] And the addition of shrubs and trees also increases aboveground carbon sequestration by as much as 1.5 to 5 tons of carbon per hectare per year, depending on site, soil characteristics, and species involved.[42] Soil carbon benefits too. A study in Florida found greater rates of carbon sequestration and storage at all tested soil depths in silvopastoral systems than on adjacent open pastureland.[43]

Silvopastoral system at Reserva Natural El Hatico, Colombia

Grazing Management

Good grazing management, particularly stocking animals at rates that avoid overgrazing, is important for raising overall productivity. Different types of soils, grasses, and regions can support varying amounts of grazing. A moderate amount of grazing for the land can stimulate plant growth, maintaining or improving overall productivity. But overgrazing the land will damage the soil, reduce forage production (and thus overall productivity), and diminish soil carbon levels.[22] An estimated 48% of grassland in Africa used by livestock is degraded, in part due to overgrazing, and could be better managed to increase production levels.[23]

Further, well-timed grazing ensures forages are grazed at their peak nutritional value. Timing the "cut," as this is sometimes referred to, is essential for maximizing the quality of feed resources and improving feed efficiency.[44]

Moving cattle between different sections of a pasture can also increase the proportion of forage consumed by animals (the utilization rate) by ensuring that no area of pasture goes ungrazed. This system of *rotational grazing* (also referred to as adaptive or regenerative grazing, among other terms) is often claimed to increase forage production, enable higher stocking rates, and improve carbon stocks compared with *continuous grazing*, in which cattle graze in a large area and are moved less often. However, the evidence for this advantage is mixed. Whereas some studies have found notable carbon sequestration benefits[45], other rigorous studies have uncovered no effects.[22]

Although controlling where and when cattle graze has important benefits, grazing practices must also be balanced with their potential negative impacts on wildlife. For example, introducing fences into landscapes to enclose cattle can harm wildlife populations, potentially killing some through entanglement and preventing wildlife from accessing seasonal feed sources.[46] In one notable case, a proliferation of fencing on the vast East African savannahs is risking some of the globe's most impressive large mammal migrations.[47]

Advances in precision livestock grazing are creating opportunities to reduce impacts on wildlife and implement rotational grazing, even in terrain where traditional fencing is not practical. "Virtual fences" can be established whereby GPS collars fixed to animals restrict movement using a combination of sound and electric shocks. The boundaries of these "paddocks" can be digitally defined on any web-connected device. And motion detectors fitted to GPS collars can monitor animal feeding, providing ranchers with information to better understand and manage animals' grazing behavior.[48]

Mechanized cutting can also achieve many of the results of good grazing management by harvesting the forage when nutrient quality is highest and sufficient growth remains to encourage rapid recovery.[49] Cut grass can be fed fresh to animals or used for the production of hay or silage, whereby the grass is fermented and preserved to be fed to animals during periods of pasture inactivity, such as in winter in the northern hemisphere or during dry seasons in the tropics.

Crop-Based Feeds

The use of crop-based feeds has large potential to increase productivity and reduce the land requirements of production. Using crop-based feeds raises productivity in two chief ways. First, it can increase the amount of feed produced per unit area, as crops like corn and soy often have higher yields than forage grasses. For instance, feed crops in the United States produce over 10% more dry matter than high-yielding forage such as alfalfa would on the same land.[50]

> Improving feed quality is among the most powerful ways to reduce GHG emissions from the livestock sector.

Second, crop-based feeds can improve animal yields and feed efficiency by improving the nutritional quality of the feeds. The best use of crops as feed is in the form of concentrates, a blended feed that typically includes grains, legumes, cereals, and vitamin supplements, designed to provide an ideal mix of nutrients. Feeding cattle just crop by-products, such as leaves and stalks (referred to as stovers), and individual crops, as is commonly done in SSA, does not provide the same level of nutrition. Cereal stovers, for instance, tend to have low digestibility.[21] Concentrates, by contrast, can be incorporated into many different production systems and used as supplemental feed. For example, they can improve yields of lactating dairy cows or be fed to beef cattle being fattened for slaughter in specialized feedlot systems such as those in North America or Argentina.

Crop-based cattle feed

Countries that use crop-based concentrates have seen major reductions in the environmental footprint of production. Since 1944, the shift in the US dairy industry from exclusively forage-based production toward increased use of crop-based feeds (along with advances in animal genetics, crop yield improvements, and other factors) has been key to reducing feed use per unit of milk by 77%, land use by 90%, water use by 65%, manure production by 76%, and GHG emissions by 63%.[51]

Even though concentrates require additional land for growing crops, they typically reduce net land use. In most cases, the additional land for crops is more than offset by the pasture area saved from the higher yields of crops and improved nutritional quality — and therefore feed efficiency — associated with crop-based feeds. A meta-analysis of life-cycle comparisons between beef production systems that were primarily pasture-based and those that used crop-based feeds estimated that pasture-based systems use about 35% more land.[52] Similarly, a modeling study projected that increased use of crop-based feeds, coupled with 40% higher crop yields and 20% higher livestock productivity than expected under a business-as-usual scenario, would result in an almost 50% contraction in grazing land in Africa by 2050.[53]

In addition, animals fed concentrates also can be, and often are, fed crop by-products such as crop residues, distillers grains, and almond hulls.[54] Although by-products alone are insufficient to provide optimal diets, their use in combination with other feeds can substantially reduce the land footprint of animal feed. This is because the use of by-products does not directly increase land use but instead makes more efficient use of existing agricultural land. For instance, by-products from the Netherlands' food processing industry, which don't use additional land, account for an estimated 70% of the country's animal feed.[54]

Looking to the future, new innovations in livestock feed sources could greatly increase the land efficiency of feeds. Algae, for example, can produce several-fold more biomass and protein per hectare than typical feeds. A recent study estimated that algae, when produced using LEDs, clean energy, and other advanced technologies, could produce feed with less than 1% the land and water footprint of typical soy cultivation.[55] In addition, algae can be produced in a variety of climates where conventional agricultural production may not be productive.[56] However, algae-based feeds are still expensive and unproven at scale, requiring further innovation to become commercially viable.[56]

Lever 2: Breeds

The breed of cattle used in dairy and beef systems strongly affects productivity. Recent improvements in dairy yields in the US, for instance, were driven to a large degree by new breeding efforts, aided by advances in artificial insemination and genetics.[51]

High-yielding cattle breeds cannot simply be imported to low-yielding regions, however. Breeding efforts must also ensure that animals are adapted to local conditions. Holstein dairy cows that produce high yields in the temperate climates of Europe and North America, for example, produce less than one-third as high yields in tropical climates, in part because they lack resistance to the tropics' heat, humidity, and diseases.[57]

Most gains in yields in recent decades have occurred in developed countries, where funding, technology, and infrastructure are more readily available. As such, there remains considerable potential for breeding to improve yields in developing regions. It has been estimated that a 29% adoption rate (as in Kenya) of more-productive breeds in Latin America, SSA, and Southeast Asia could help meet projected 2030 demand for meat and milk with 16% fewer animals.[36] In addition, other breeding efforts that improve the productivity of local breeds while maintaining locally adapted traits may also have large benefits.[58]

Slow rates of genetic change typically imply long periods of time for breeding to bear fruit, but modern breeding technologies offer the potential to accelerate and improve the process. Advances in genomic selection and bioinformatics enable breeders to target genes associated with desirable traits and to better identify traits in different breeds.[58] In addition, scaling up the use of artificial insemination enables more farmers to use genetic material from the best cattle. Finally, breeders and geneticists are beginning to develop transgenic and gene-edited livestock that are hardier and more productive.[59] Yet given the low rates of adoption of such practices, even in countries such as the US and UK, new efforts will be needed to increase their use and benefits.[x]

Lever 3: Animal Health

Animal health and welfare are vital for a productive and ethically responsible livestock system. Cattle that are well cared for have higher growth rates, higher calving rates, and lower mortality rates. This translates to higher yields, feed efficiency, and overall productivity. Two primary components of ensuring animal health and welfare are shelter and veterinary care.

When livestock lack proper shelter, exposure to heat, cold, mud, or overcrowding creates stress and reduces productivity. Providing shade can increase animals' weight gain by as much as 20%, milk production by 12-15%, and conception rates by 50%.[60] By contrast, prolonged exposure to cold reduces feed efficiency and weight gain.[61,62] Muddy conditions also increase the energy maintenance requirements of cattle, reducing weight gain and increasing feeding costs.[63]

x Personal communication, J. Capper, May 2019.

Veterinary care is also essential. Approximately 20% of livestock production is lost due to animal diseases.[64] Fortunately, treatments and preventative measures for many diseases can greatly reduce losses. For example, the number of cases of mastitis in the UK decreased more than 70% from the 1960s to the late 1990s as best veterinary practices spread.[65] Developing regions characterized by smallholder and pastoral systems have seen some improvement in animal health with the adoption of veterinary drugs, but not at the same magnitude as developed countries.[65]

PUBLIC POLICY AND THE PRIVATE SECTOR:

INCENTIVIZING INTENSIFICATION AND FULFILLING ITS ENVIRONMENTAL POTENTIAL

Intensification of low-productivity systems, especially in regions where demand for beef and milk is projected to grow rapidly, is key to furthering the decline of global pasture. However, spreading the livestock revolution will entail making systemic changes to these regions' production systems and must overcome barriers to the widespread adoption of new practices.

Livestock producers face upfront costs and limited incentives to intensify when land is inexpensive in relation to other inputs.[66] They also face downside risk, uncertainty about future benefits, implementation costs, and credit constraints when adopting new practices.[49]

Driving systemic intensification is not the only challenge, however. The benefits of producing more meat and milk per unit area do not automatically accrue to the environment, at least not at a local level. Although intensification does indeed have reliable land-sparing benefits globally, it does not guarantee these benefits at smaller scales and can even carry environmental risks in the form of rebound effects — greater land-use change as a result of production becoming more profitable.[66,67]

What are needed, then, are targeted efforts by the public and private sectors to both incentivize intensification and fulfill its environmental potential. These can be grouped into four categories: providing direct financial and technical assistance to producers; increasing access to input markets; land-use planning; and private-sector agreements. While these categories are not exhaustive (other efforts, such as investing in agricultural research, are valuable as well), they are among the most important for spreading the livestock revolution and continuing the global decline in pasture area.

Direct Financial and Technical Assistance

Providing direct government support to producers in the form of access to capital, intermediate inputs such as feed, and technical assistance can greatly increase the adoption of productivity-enhancing practices.[21] Access to capital can be a barrier to intensification since investments in productivity often have long payback periods and are therefore risky.[xi] For example, in Colombia, lack of access to loans or other financing is a barrier to adopting silvopastoral systems. One study estimated it can take three to six years for producers to recoup their investment in silvopastoral systems for cattle ranching.[33] And not all producers are willing to work with such a long-term investment horizon.

Subsidized loans or other government guarantees are therefore needed. These enable farmers to make investments in productivity with similarly long payback periods or that appear risky.[40] Credit availability can also be used as a lever for enforcing compliance with environmental regulations, as demonstrated in Brazil, which began in 2008 to require rural areas in the Amazon to comply with environmental requirements in order to receive credit.[68]

> Spreading the livestock revolution entails systemic change to regions' production systems and must overcome barriers to the widespread adoption of new practices.

State subsidies, price guarantees, and other public support programs can also reduce the cost of productivity-enhancing inputs, such as optimized feeds, thereby increasing their adoption. Buying high-quality supplemental feeds, such as the concentrates used for beef finishing operations, is one of the best ways to increase productivity but is also expensive. Feed is the second highest cost for feedlots in the

xi R. Garrett, personal communication, December 6, 2018.

United States.[69] Many developed countries have created public support programs, such as crop subsidies or insurance plans, to increase grain production. As a result of such programs, the productivity of grain crops, which provide a significant share of animal feed, has risen and prices have fallen.[70]

Because the increased use of crop-based feeds can exert pressure to convert land to cropland, it may be necessary to pair support for it with land conservation policies and programs. Examples include incentives in parts of the United States for farmers not to convert wetlands or highly erodible soils to crop production.[71]

Finally, farmers' access to knowledge strongly influences the adoption of productivity-enhancing practices.[72] Programs that transfer knowledge to farmers and ranchers, such as public agricultural extension programs, often improve their management skills and can also provide assistance for adopting new inputs or practices. For example, one study found that access to technical assistance is a key determinant of whether Brazilian ranchers' adopt integrated crop-livestock systems, which boost productivity.[73]

Physical Infrastructure and Access to Input Markets

Systemic intensification requires that more producers have access to productivity-enhancing inputs, such high-quality animal feeds, high-yielding grass seeds, and fertilizer. In turn, this requires physical infrastructure to connect producers to input markets.

Infrastructure such as roads, ports, and processing facilities have been shown to increase livestock productivity.[72] Better road access in rural Kenya, for example, was shown to increase market participation, fertilizer use, and agricultural yields.[74] In Mato Grosso, the largest soy- and cattle-producing state in Brazil, cattle producers who are closer to slaughterhouses have higher rates of intensification, which is linked to reduced forest loss.[66] More broadly, producers closer to cities have higher rates of adopting best practices. This illustrates how proximity to agricultural extension agents and other sources of technical assistance helps producers improve management.

However, road-building efforts must also aim to minimize these corridors' harm to habitats and ecosystem health. The majority of planned road expansion is in developing countries, particularly in Africa and Latin America, and is likely to lead to severe habitat fragmentation and wildlife loss in biodiversity hotspots.[75] Nonetheless, when well managed and sited in places already settled by people who have low agricultural productivity due to poor market access, some of these road improvements could help drive productivity increases and thus preserve these same habitats.[76]

Policy makers and other conservation stakeholders must carefully manage the risks of rebound effects that come with increased access to input markets. Lower input costs can make ranching more profitable and thereby expand production and land-use conversion. This effect underscores the importance of coupling support for intensification with prudent land-use policies.

New road infrastructure in Luanda, Angola

Land-Use Planning

Land-use planning is needed for both encouraging intensification and realizing its environmental benefits. Intensification's environmental benefits and costs can vary by location. For example, in Brazil, livestock intensification reduced pasture area when it was practiced on land far from forested areas, but did not when it occurred on frontier lands, such as those at the forest margins.[68,77] Land-use planning aims to promote desirable social and environmental outcomes, in part by directing agricultural and infrastructure development toward the best-suited areas.

One important goal of land-use planning is to make land conversion expensive for producers, thereby making intensification financially more appealing. For example, an assessment of cattle ranching in the Brazilian Amazon found that intensification was far less likely to be profitable in the central Amazon than in the Cerrado or Atlantic Forest regions, where land prices were two to three times higher.[78] In addition, the adoption of feedlots (e.g., in North America and parts of Argentina) is often attributed partly to higher land prices that make the economics of intensification more favorable than pasture expansion.[69]

Policies that increase land-conversion costs include those that tax land ownership, impose fees or fines for deforestation, or enforce protected-area restrictions.[12] Brazil's Priority List, for example, increases environmental monitoring and enforcement and reduces the availability of agricultural credit to municipalities with high deforestation rates. The measure makes land clearing more expensive, causing farmers to invest in productivity improvements instead of pasture expansion.[79] Government investment in enforcing these policies is also key: for instance, weak government enforcement of Brazil's Forest Code is thought to substantially increase deforestation.[80] Similarly, policies can provide positive incentives, such as tax breaks, for landowners who support conservation efforts. For example, South Africa allows landowners to deduct from their taxable income the value of land in a privately protected area that meets specific criteria.[81]

In some regions, undoing policies that encourage land expansion is as important as creating new ones that support intensification. The British government's support for grazing sheep in the "sheepwrecked" uplands has come under criticism for contributing to severe soil erosion. Without subsidies, few of these operations would be economically viable, and their operation maintains grassland systems on what would otherwise be more densely covered moorland and forest.[82] In Brazil, settlement policies have encouraged families to convert frontier land (e.g., in forested regions) to farms and ranches in order to gain title to that land. Many families set up ranching operations for this purpose while actually producing very little beef, leading to substantial land clearing and low productivity.[12]

Private-Sector Agreements

The responsibility for transitioning to more productive and environmentally beneficial livestock systems lies not just with government, but with the private sector as well. Given the high degree of market concentration in the livestock sector (just four corporations slaughter about 80% of US beef, for instance), shifting the procurement and supply chain practices of only a few companies could have powerful effects.[83]

As global livestock production transitions to greater reliance on supplemental feeds, industry-wide agreements and standards around crop-based feeds and ranching will be critical for limiting agricultural land-use change. New initiatives can be based on existing industry agreements, many of which aim to stop sourcing products from farmers who contribute to deforestation.

It should be noted, however, that such initiatives have had mixed success. After major meat-packing companies in the Brazilian Amazon signed zero-deforestation cattle agreements, major slaughterhouses began purchasing cattle from properties with lower deforestation rates.[84] Even so, these agreements had little overall positive impact on land use since deforestation increased on properties that were not initially covered by the agreements.[85] This failure suggests that industry agreements that cover the entire supply chain and entail monitoring all producers — often termed "jurisdictional" approaches — are needed to substantially reduce deforestation.[85]

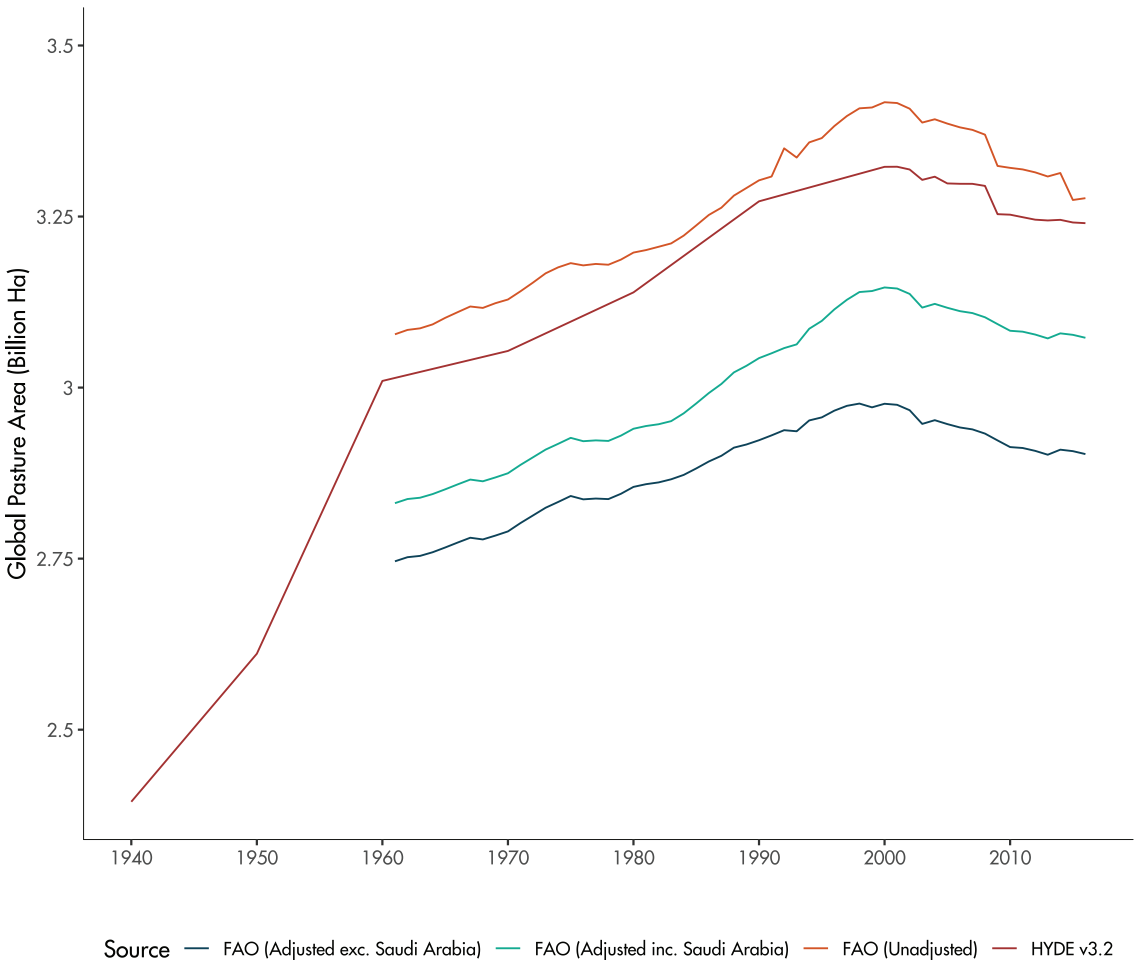
Industry standards are also most effective when supported by government policies. Governments can improve the effectiveness of industry agreements by facilitating information sharing across supply chains, paying compliance costs for small producers who otherwise might not seek certification, and ensuring that industry efforts cover all producers, especially those most likely to convert new land to production. In addition, governments can use the threat of regulation to encourage industry to develop strong voluntary standards.[86]

Less evidence exists that other types of voluntary private sector initiatives, such as company pledges and codes of conduct, effectively increase productivity while reducing land-use change. Public company pledges, such as attaining zero-net deforestation in a supply chain, are increasingly common, but a large percentage (20%–25%) of companies who make such pledges do not have action plans to achieve them.[86] And although some corporate supplier standards have had positive effects — such as Starbucks' Coffee and Farmer Equity (C.A.F.E.) Practices program, which has helped coffee farmers increase yields — corporate procurement data are often proprietary, and thus there is insufficient evidence to assess their effectiveness.[86]

In general, the impact of private-sector efforts is far from certain. But when such efforts take a jurisdictional approach, they can be an important tool for raising livestock productivity and minimizing land-use change.

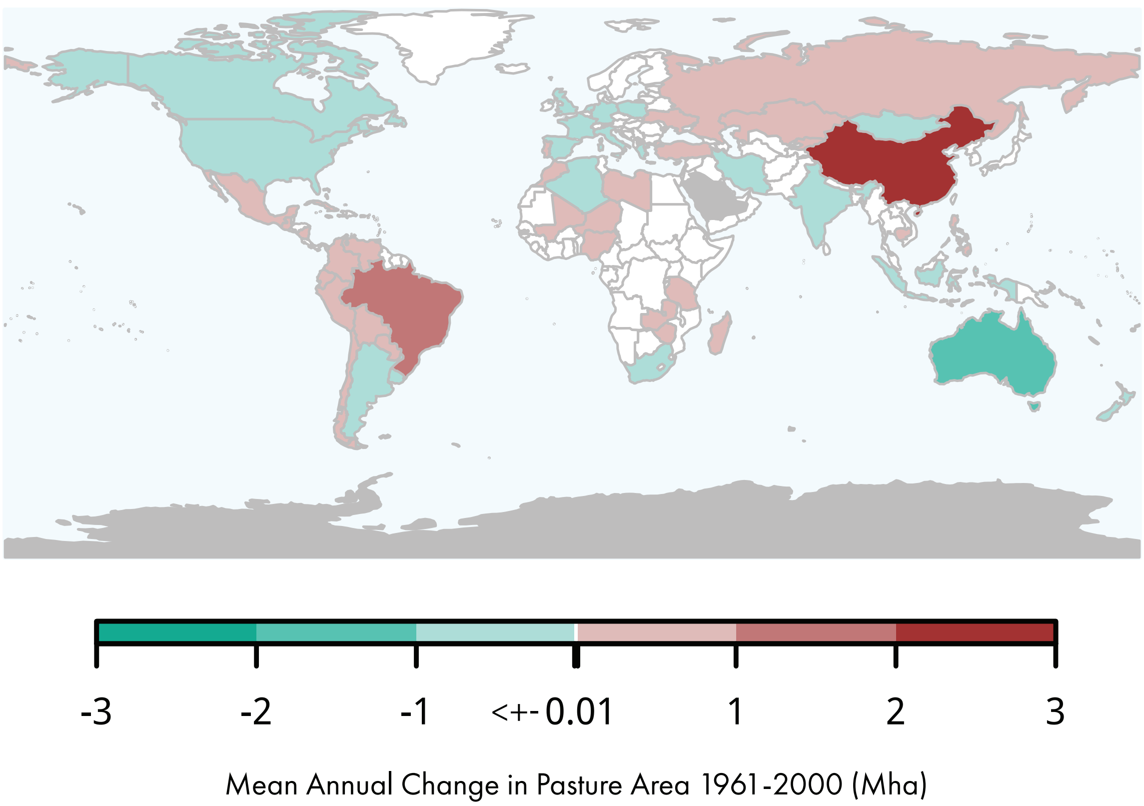
APPENDIX 1: SUPPLEMENTARY FIGURES

Figure A1: HYDE Data Corroborates Pasture Decline Shown in FAO Data



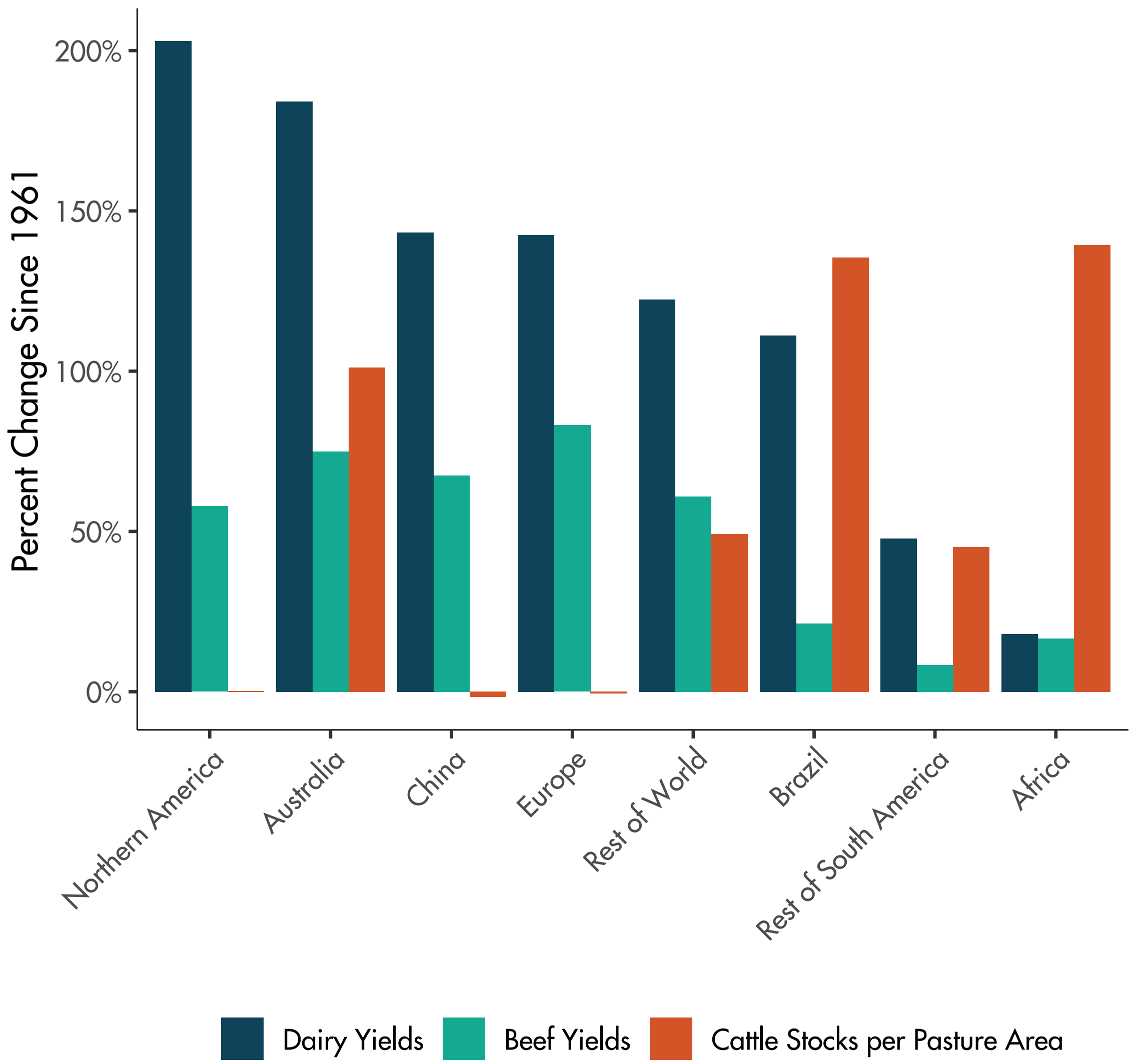
Sources: FAO (2019), Klein Goldewijk et al. (2017)

Figure A2: Pasture Area Change Worldwide, 1961–2000



Omitted countries shaded gray.

Figure A3: Change in Animal Yields by Region, 1961–2013



Omitting Former Soviet Union. Source: FAO (2019).

APPENDIX 2: DATA AND METHODS

Pasture Area

- Figures and calculations of pasture area were derived from the FAOSTAT "Land Use" dataset on "Land under permanent meadows and pasture" for all countries. Data were accessed May 3, 2019. All calculations and figures use data that have been adjusted, as described below.
- The FAO notes that several countries changed their methodologies for measuring or reporting pasture area during the study period. Several of these countries also experienced one-year percentage changes in pasture area outside the 99.9 percentile range. For Ecuador, Hungary, and Japan, we assumed these outlier change values were entirely caused by changes in reporting or measurement. Thus, for each year in which there was an outlier change value, we assigned the previous year's value and then adjusted future values so that subsequent year-to-year changes remained the same as originally reported by FAOSTAT.
- Pasture area was reported just for Sudan in 2010 and for both Sudan and South Sudan starting in 2011, with a steep drop in pasture area of approximately 35 million hectares from 2008 to 2009. We assumed that the 2008–2009 decline was due entirely to measurement or reporting problems, and accordingly set the 2009 value to that of 2008, adjusting Sudan and South Sudan's values upward post-2010.
- When Eritrea gained independence from Ethiopia in 1993, total pasture area across the countries reportedly declined more than 50%. We adopted the same approach as for Sudan and South Sudan, assuming that pasture area did not change significantly from the year before the split to the year after.
- For Australia, FAOSTAT reports a drop in pasture area from 2014–2015 that is approximately 20 times greater than the average rate of decline in the previous 30 years. Personal communication with FAO staff indicated that: "The latter acceleration is not 'real.' It is likely linked to a change of reporting methodology in Australia." Starting in 2015, Australia began to report only land owned by ag-

ricultural businesses over a certain value. We therefore assumed that Australian pasture area changed from 2014 to 2015 at the 30-year average rate instead. Some analyses also suggest that a portion of the pasture decline in Australia resulted from transferring pastoral land from nonindigenous leases, which are included in FAO reporting, to indigenous pastoral leases and conservation reserves, which are not included. According to Van Etten (2013), land under indigenous (aboriginal) leases and conservation reserves increased by 12.54 million hectares between 1955 and 2008.[87]for many, making a profit from pastoralism is no longer a priority. For the central rangelands of Western Australia, these groups have included: government agencies, who have purchased some 9% of pastoral leases by area; private conservation organisations (<1% purchased Assuming that there was zero area under these land types before 1955, we calculated the annual conversion rate by dividing 12.54 by the number of years in the time period (1955–2008) and then adding that conversion rate to each Australia observation from 1961 to 2016.Pasture area increased 10% for countries in the former Soviet Union from 1991 to 1992, following the dissolution of the USSR. This is a large change in absolute pasture area that is at odds with assessments of farmland abandonment, such as those of Prishchepov et al. (2013).[88] We therefore replaced pasture areas for the USSR and former Soviet Union countries with pasture area values from HYDE 3.2, linearly interpolating between years.[11] In this model, pasture area for the former Soviet Union still increased after 1990, but less sharply than in the FAOSTAT data.

- Japan stopped reporting "Land under permanent meadows and pastures" in 2000 and started reporting only "Land under temporary meadows and pastures" in 2001. We used this latter data series for pasture area for Japan after 2000.

Production

- Figures and calculations of pasture area were derived from the FAOSTAT "Livestock Primary" dataset for all countries. Data were accessed May 3, 2019. All calculations and figures use data that have been adjusted, as described below, unless otherwise noted.
- Hong Kong reported a value of 10,000 for beef yields multiple years — roughly twice that of any other observation. We assumed these values to be reporting er-

rors or NAs (data not available). For production quantity and number of animals slaughtered/milked, we also found values of 1 and 0, which may represent NAs or reporting errors.

- Outlier values and NAs were imputed using the last observation carried forward (LOCF) method, implemented with the "zoo" package in R.[89,90]

Additional Notes on Figures

- Figure 2: White denotes countries that saw between –1,000 and +1,000 hectares of average pasture change per year.
- Figure 3: All countries were assigned their 2018 World Bank income group throughout the 1961–2016 time series.
- Figure 5: Countries were categorized by climate zones as described in Godde et al. (2018).
- Figure 6 was created using adjusted pasture and production data. It omits former Soviet Union countries owing to data-consistency issues with production and animal stocks.
- Figure 7 was created using unadjusted data from FAOSTAT "Food balance sheets" on "Production Quantity" and "Domestic supply quantity" for "Bovine meat" and "Milk - Excluding Butter" for "World + (Total)."
- Figure 8 was created with adjusted production data. Yield was calculated for income groups by dividing the total production for the income group by the total number of cattle slaughtered or used in dairy production. Former Soviet Union countries were omitted because no pre-1992 yield data were found for individual countries that were members of the Soviet Union (e.g., Azerbaijan).
- Figure 9: Pasture Expanded and Pasture Contracted designations were based on our own analysis of FAOSTAT data and refer to whether pasture area was higher or lower in 2016 than in 1961.
- Figure 11 was created using unadjusted data from FAOSTAT "Food balance sheets" on "Production Quantity" and "Domestic supply quantity."
- Figure 12: All projections were standardized using the same 2010 baseline (the adjusted FAOSTAT value).
- Figure A1: The FAO (unadjusted) data series used was the FAOSTAT "Land Use" dataset "Land under permanent meadows and pasture" for "World + (Total)."
- Figure A2: White denotes countries that saw between –10,000 and +10,000 hectares of average pasture change per year.

- Figure A3 was created with adjusted production data. Yield was calculated for geographic groups by dividing the total production for the group by the total number of cattle slaughtered or used in dairy production. Former Soviet Union countries were omitted.
- All figures were created in R using the packages ggplot2 and rworldmap.[90–92]

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ABOUT THE AUTHORS

Dan Blaustein-Rejto

Dan is Senior Food & Agriculture Analyst at the Breakthrough Institute. His research focuses on the potential of policies and practices in the agricultural sector to mitigate climate change. Dan holds a Master of Public Policy from the University of California, Berkeley and a BA from Brown University.

Linus Blomqvist

Linus is Director of Conservation and Food & Agriculture at the Breakthrough Institute and a co-author of An Ecomodernist Manifesto. His research focuses on strategies to address the twin challenges of meeting food demand and protecting biodiversity. Linus holds a Master of Environmental Science from Yale University and a BA from Cambridge University.

James McNamara

James is a conservation scientist whose work sits at the intersection of economic development and wildlife conservation. He has worked extensively on the illegal wildlife trade, notably in West Africa and Southern Asia, and is particularly interested in understanding how agricultural innovation can help improve rural livelihoods while also protecting nature.

Kenton de Kirby

Kenton is Content Director at the Breakthrough Institute. He is a social scientist with a longstanding interest in the nexus of environmental politics and human cognition.

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THE BREAKTHROUGH INSTITUTE
436 14TH ST
SUITE 820
OAKLAND, CA 94612

WWW.THEBREAKTHROUGH.ORG
TWITTER: @THEBTI