CGIAR Initiative on Livestock and Climate

Climate outlook for rangelands in Senegal

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Executive summary

By the year 2050, changes in climate are likely to cause significant impacts on rangelands and agriculture and livestock systems throughout West Africa, among other heavily impacted regions of the world. Climate change is expected to cause shifts in global weather patterns, leading rainfall to decline in some parts of West Africa, and to remain similar to present rainfall in others.

In the Republic of Senegal, climate change may have minor impacts on annual rainfall and the production of biomass and livestock in the drier rangelands of the northern Sahelian Zone (current average annual rainfall < 500 mm/yr). These drier arid to semi-arid rangelands are projected to largely maintain their current rangeland and livestock productivity through 2050. However, in wetter rangelands in southern Senegal (current rainfall > 500 mm/yr), declining rainfall and increasing aridity may severely reduce rangeland productivity, with a projected loss of over 60% of current rangeland biomass production. These changes in climate would significantly reduce the productivity of livestock and rainfed crops in the Sudano-Sahelian and Sudanian Zones of southern Senegal.

The precise eventual impacts of climate change are difficult to predict, yet these projections indicate that agricultural producers and livestock keepers in southern Senegal should prepare themselves for coming changes, while keeping hope that climate change adaptation can and will maintain rural livelihoods. The projections do not include changes in droughts, floods, or other extreme weather events, nor changes in land use or land management. The need for drought- and flood-proofing and sound management of land and livestock is now greater than ever, and these efforts can soften the impacts of climate change through appropriate adaptation of agro-livestock systems.

Long-term livestock production potential may be strong in the drier northern rangelands of Senegal, although this potential appears likely to weaken in the southern rangelands. Agro-climatic suitability for more sustainable livestock production may increase overall throughout the nation, indicating that livestock and rangelands will remain essential sources of income, livelihoods, nutrition, and environmental goods in Senegal for the foreseeable future. Rangelands and livestock can significantly assist smallholder producers in Senegal to adapt to and mitigate the anticipated impacts of climate change on economic activity and livelihoods. Projected changes in rangeland productivity in response to shifting rainfall and aridity provide a useful backdrop for development of initiatives to strategically plan and achieve sustainable management in rangelands and the larger agricultural sector, toward maintaining rural livelihoods and the economy in Senegal in spite of ongoing climate change.

Background

Most of the Republic of Senegal is rangelands, and livestock contribute 36% of agricultural gross domestic product (GDP) while employing 30% of the total population (1). Rangeland livestock systems make large contributions to rural livelihoods, nutrition, economy, and environmental goods in Senegal (1), and these current contributions may become more important under climate change (2). As in much of West Africa, significant changes in climate are projected in southern Senegal (3) in terms of decreasing rainfall and increasing aridity.

Climate impacts on rangeland ecosystems and livestock production, and the ripple effects of these impacts throughout the agricultural sector, may negatively affect the livelihoods of smallholder producers and the national economy. Ecosystem simulation models can project rangeland ecosystem functioning under forecasted future climate conditions. Here, the G-RANGE global rangeland model (4,5) provides projections of rangeland biomass production and other ecosystem functions, as a result of changes in rainfall and aridity up to the year 2050. Simulation model projections (4) are useful to better understand and prepare for the possible changes in agriculture and livestock systems over coming decades.

The G-RANGE global rangelands model is run forward from a long-term equilibrium (2,000 years) in the year 1951, through the year 2050. The projected changes in rangeland ecosystems are primarily caused by rainfall and temperature forecasts from seven different climate models: BCC (China), CSIRO (Australia), GFDL and GISS (USA), HadGEM2 (UK), IPSL-CM5 (France), and MIR-CGCM3 (Japan) (6-12). Here, the seven CMIP5 climate models are run under a relatively positive scenario for global greenhouse gas (GHG) emissions (RCP 4.5), and run again under a negative scenario (RCP 8.5), creating a total of 14 simulations of future climate and ecosystems. Changes in aboveground rangeland biomass production and other ecosystem outcomes produced by the 14 simulations are averaged to provide the projections presented here.

Since each climate model forecasts somewhat different rainfall and temperature, each simulation produces somewhat different changes in rangeland ecosystems. The projections reflect the best of our scientific understanding, but they are unlikely to be perfectly accurate. Extreme droughts, flooding events, and other system shocks are likely to become more frequent, but since no predictions are available for these unpredictable events, they cannot be represented. Changes in land use and land management are not included either, as it is unclear how these factors will change along with social and economic systems and values.

About this brief

The projections presented in this brief can be used first to better understand what major changes in rangelands, livestock, and agriculture are relatively likely in certain rangeland regions or areas by 2050, as a result of climate change. Other appropriate uses include strategic planning of land use; identifying management practices that may improve productivity and sustainability in these areas; and setting policy and programmatic priorities for sustainable development. Projected values for any local area may have high uncertainty, and the projections for a certain local area should never be used at local level, for any purpose. The most appropriate scale for interpreting and using these projections is at a national or sub-national level such as a region or province.

The rangeland projections focus first on trends in aboveground rangeland biomass production through 2050, which result directly from changes in rainfall, temperature, aridity, and the concentration of carbon dioxide (CO_2) in the air (aridity is the combined effects of rainfall and temperature). These factors can also cause further changes in vegetation structure and composition, bare ground, and soil carbon stocks and dynamics. Changes in rangeland ecosystems may significantly influence agricultural and livestock systems, with impacts on feed supply rates, long-term livestock production potential, agro-climatic suitability for livestock and crops, the sustainability of rangeland production, and the ability to store carbon in soils, land, and ecosystems. Suitability for livestock production is defined here in terms of the productivity of livestock compared to rainfed crops, as well as the sustainability of livestock production in terms of land degradation. Climate impacts in rangelands can help identify the most appropriate and feasible sources of rural livelihoods and relevant management practices under climate change. As a result, projected impacts can help inform policies and initiatives in support of the sustainable intensification of agriculture and livestock production in Senegal.

Year 2050: Climate change effects on rangelands and their larger impacts

By 2050, rangelands in Senegal are projected to change in the following ways in response to shifts in climate, rainfall, temperature, aridity, and atmospheric CO_2:

Rangeland biomass production

- In drier northern rangelands (current rainfall < 500 mm/yr) of Senegal, rangeland biomass production is projected to remain similar to current levels, on average.
- In the wetter southern rangelands (current rainfall > 500 mm/yr), rangeland production is projected to decline severely, losing approximately 60% of current biomass production by 2050.
- These trends do not include the negative impacts of droughts and floods, nor positive or negative changes in land use or management.

Livestock feed supply

- The total local feed supply should remain consistent in the drier northern rangelands (< 500 mm/yr).
- The total local feed supply may contract severely in wetter southern rangelands (> 500 mm/yr).

Year 2050: Climate change effects on rangelands and their larger impacts

Potential and suitability for livestock production

- In the drier northern rangelands (< 500 mm/yr) the potential and suitability for livestock production should remain similar to the present.
- In wetter southern rangelands (> 500 mm/yr) livestock production appears likely to decline with lost biomass production, though the suitability, sustainability, and importance of these rangelands for livestock production may increase.

Rangeland vegetation structure and cover

- No major changes in vegetation cover are projected, such as expansion of bare ground or large invasions of woody shrubs and trees, in drier northern rangelands (< 500 mm/yr).
- The wetter southern rangelands (> 500 mm/yr) may see some woody encroachment, which could be accelerated by droughts, floods, and management.

Soil and ecosystem carbon storage potentials

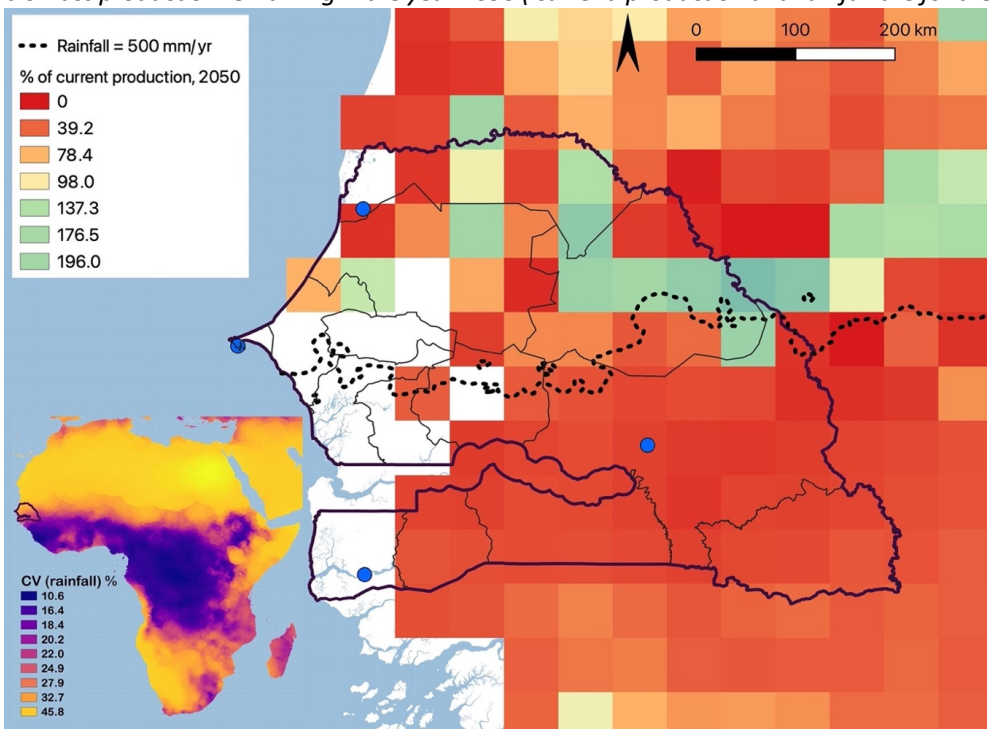
- Soil organic carbon and ecosystem carbon storage potential are likely to remain similar to current levels in drier rangelands (< 500 mm/yr) of northern Senegal.
- In wetter southern rangelands (> 500 mm/yr) large losses of productivity and soil organic carbon indicate that the ability to store carbon in soils or rangeland ecosystems may decline severely.

Projected changes in rangeland ecosystems

In drier rangelands in the north of Senegal (current rainfall < 500 mm/yr), rangeland biomass production is projected to remain similar to current levels through the year 2050 (Table 1, Figure 1). These dry savanna, semi-desert, and desert portions of northern Senegal will likely have a similar supply of livestock feed from local sources by 2050 as they have currently. Biomass production may increase in some localities or on average, although climate forecasts in the area are not clear. The potential and suitability for livestock production and other agricultural livelihoods in these drier rangelands is not likely to change, and livelihoods feasible at present may continue relatively uninterrupted. No major changes are expected in terms of vegetation composition, bare ground or soil organic carbon stocks (4). Total ecosystem carbon storage rates are likely to remain similar to their current, low levels.

In contrast, in wetter rangelands in the south of Senegal (current rainfall > 500 mm/yr), rangeland biomass production is projected to decline severely by the year 2050 (Table 1, Figure 1). Rangelands in these areas are projected to lose approximately 66%, or two-thirds, of their current biomass production. Such a decline would have major impacts on livestock and agriculture in general, as feed supplies and stocking rates contract. Meanwhile, the suitability of these rangelands for livestock production will likely increase in comparison to the present. Bare ground is not projected to change although a slight increase in woody cover of ~5% (4) is possible due to increasing aridity. Climate change may reduce soil organic carbon stocks substantially (4), along with carbon storage potentials of soils and entire ecosystems. Achieving global climate change mitigation through sequestration of carbon in soils or whole ecosystems could be exceptionally challenging in these rangelands, although alternative mitigation of system GHG emissions is available.

Figure 1: Projected changes in rangeland biomass production through 2050, shown as the percentage of current biomass production remaining in the year 2050 ('current' production and rainfall are for the year 2000).



The dashed line (- - -) divides rangelands with current annual rainfall < 500 mm/yr (to the north; Sahelian Zone) and > 500 mm/yr (to the south; Sudano-Sahelian and Sudanian Zones). Solid lines are the regional boundaries. Inset map shows the coefficient of variation (CV; in %) of annual rainfall; the most arid rangelands have CV > 33% (15).

Table 1. Climate change projections for rangelands in Senegal, and their implications for livestock production and management. Impacts are separated for the drier northern rangelands (current rainfall < 500 mm/yr), and wetter southern rangelands (> 500 mm/yr) of Senegal.

	Current rainfall	
	Rainfall < 500 mm/yr (arid to dry semi-arid)	**Rainfall > 500 mm/yr** (moist semi-arid to sub-humid)
Rangeland biomass production (total net primary production [NPP])		
Average % of current* biomass production in 2050	103.53%	33.70%
Average change from current* to 2050	+3.53%	–66.30%
Implications for livestock production and management		
Biomass production (total NPP)	Similar to currently	Large loss
Livestock feed supply (local, total)	Similar to currently	Large loss
Livestock production potential**	Similar to currently	Large loss
Livestock suitability	Similar to currently	Large gain
Crop productivity (rainfed)***	Similar to currently	Large loss
Woody cover	Similar to currently	Small gain
Soil organic carbon (SOC)	Similar to currently	Large loss
C storage potential (total = ΔNPP + ΔSOC)	Similar to currently	Large loss

*'current' biomass production (total NPP) is for the year 2000

**livestock production potential = livestock feed supply + suitability for livestock (as compared to rainfed crops)

***for crops currently grown—does not include switching to drought-tolerant crops

Climate change impacts and their implications for rangelands

Drier rangelands (Sahelian Zone)

In drier, arid to semi-arid rangelands (current average annual rainfall < 500 mm/yr, i.e., the Sahelian Zone) in northern Senegal, no major changes in climate or rangelands are projected. The productivity of the present mix of livestock and crops may not change fundamentally through 2050, although droughts, floods, and management will have their effects. Rainfed crops will continue to have limited feasibility, as ever in such dry regions, although crops are an important aspect of livelihoods for some (1,14). As a result, livestock and their products should remain key sources of income and livelihoods in the area over coming decades.

On average across the entire dry Sahelian Zone of northern Senegal, the low chance of large losses in rainfall indicates that direct climate impacts may be modest, with minor effects on rangeland biomass production and the larger livestock and agriculture sectors (Table 1). Changes in climate are difficult to forecast in the Senegalese Sahel, however, because different climate models disagree on how weather currents and rainfall will change through 2050. These disagreements among climate models (here, seven models) create a patchwork of vastly differing projections from positive to negative, sometimes over short distances (Figure 1). This high local uncertainty means that local values are unlikely to be accurate for any exact local area. Projections for specific individual localities should not be used directly in calculations, formulation of recommendations, or otherwise. Rather, the average projection for the entire Sahelian Zone of northern Senegal (Table 1) is the best estimate. These dry rangelands may benefit from 'CO_2 fertilization', the direct and positive effect of rising atmospheric CO_2, which increases water use efficiency and drought tolerance, thereby benefitting rangeland and crop biomass production. This positive effect of CO_2 fertilization helps counteract the negative effects of increased temperature and aridity.

Given these trends, the overall livestock production potential of Sahelian rangelands in Senegal is more likely than not to remain similar to the present. Rangeland biomass production, the feed supply, and appropriate stocking rates may be much like today. As they are not projected to become more or less arid, these dry rangelands should remain suitable for relatively sustainable livestock production.

In the Sahelian Zone, stocks of soil organic carbon and the carbon storage potential of soils and entire ecosystems are not projected to change, nor are vegetation structure or bare ground. However, these desert rangelands produce little biomass and store carbon at low rates—albeit over very large areas (13). Fortunately, a wide variety of effective non-land-based mitigation measures are available for agriculture and livestock systems including rangelands throughout Senegal.

Wetter rangelands (Sudano-Sahelian and Sudanian Zones)

The sharp projected decline in rangeland biomass production in wetter, semi-arid and sub-humid rangelands (current average annual rainfall > 500 mm/yr, i.e., the Sudano-Sahelian and Sudanian Zones) in southern Senegal would be highly disruptive to the livestock sector, and the larger agricultural sector. The impact felt most by farmers would be the increasing difficulty of rainfed cropping (1,14), which combined with reduced rangeland production and feed supplies, would cause substantial negative economic and livelihood impacts. Significant changes in agricultural systems may be reasonably expected by 2050. These changes may include switching to rainfed crops that are more drought-tolerant (14), increasing full irrigation of crops, and shifting from crops to livestock (2) or alternative sources of livelihoods.

The projected loss of rangeland biomass production in the semi-arid and sub-humid zones is primarily the result of declining rainfall and increasing temperature. This increase in aridity is the result of shifts in global weather currents forecasted under climate change (3). Climate change-induced aridification in the wetter rangelands of southern Senegal might look like massive degradation to the casual observer. To be precise, this would not be degradation, but a larger transformation. If rainfall declines as projected, the present-day Sudano-Sahelian and Sudanian Zones would gradually come to resemble the drier Sahelian rangelands and production systems of northern Senegal. Woody cover is projected to increase slightly (~5% cover gain) in wetter southern rangelands, an effect that might combine with aggravating factors to encourage woody browses to invade and dominate grazing lands. Woody invasions are encouraged not only by increasing aridity, but also by droughts, floods, and land use and management factors such as overgrazing and undergrazing, lack of fire management, and abandonment of croplands.

In light of these projections, the long-term overall livestock production potential of Sudano-Sahelian and Sudanian rangelands in southern Senegal may be likely to decline strongly from the present. The decline in rangeland biomass production would restrict the feed supply from local sources and necessarily reduce livestock density (unless large areas of present croplands are converted into rangelands). The decline in livestock population would severely affect rural livelihoods. At the same time, as these rangelands become more arid due to climate change, their suitability for livestock production may increase. The most arid lands are better suited to livestock than to rainfed crops (2), and resist degradation better than wetter semi-arid to humid rangelands (15), making livestock production potentially more sustainable in the driest rangelands. In contrast, rainfed cropping may become increasingly difficult as 2050 approaches and if rainfall declines as forecasted, while irrigation may become more necessary, making cropping less efficient and less sustainable. Due to the loss of rainfall caused by climate change, currently semi-arid and sub-humid rangelands in south of Senegal may be more important, suitable, and sustainable for livestock production in approaching decades as a result of becoming drier.

Climate change through 2050 may be likely to reduce carbon stocks in soils and carbon storage potentials in the wetter rangelands of southern Senegal, although a decline in livestock density would imply reduced GHG emissions from livestock. Soil storage is often the primary opportunity for carbon sequestration in rangelands (13), but declining biomass production means declining carbon inputs and soil carbon stocks (Table 1). Land management to provide global carbon mitigation through sequestration of carbon in ecosystems would need to supersede or override the negative effects of climate change in terms of declining rainfall, which may be exceptionally challenging. A wide variety of other available mitigation measures could be more feasible and effective in reducing greenhouse gas emissions from livestock systems.

Other factors likely to influence actual future changes

The projections presented in this brief do not include some factors that may have strong effects on the eventual, actual impacts of climate change. Among the most important factors are increasingly frequent extreme droughts and flooding events, which make the projections seem relatively optimistic—that is, real trends could be more negative than the projections here. Invasive species could bring unforeseen difficulties in rangelands, crops, and elsewhere. Climate change in rangelands may also reduce forage quality in rangelands with low soil nitrogen and cause shifts in rangeland vegetation (16) (for example, perennial to annual grasses, or grasses to shrubs), while more variable rainfall within each season can slow production (17). More positively, as the climate changes, rangeland vegetation could expand rapidly into newly appropriate habitats, helping to maintain biomass production. If rangeland vegetation

can keep pace with changes in climate, the projections would be relatively pessimistic, and rangelands could see weaker impacts than projected here. However, the greatest uncertainty is the human element. Land use change (rangelands to crops, crops to rangelands, etc.) and land management could further degrade rangelands and create inefficient production systems. Alternatively, planning of appropriate land use and effective land management can greatly help toward achieving climate-resilient crops and livestock.

Management, planning and policy for rangelands in response to climate change

Changes in production systems

In Senegal, a majority of the population are engaged in agriculture (58%) and many in livestock keeping (36%) (1). Livestock production has been more stable than crop production in Senegal in the face of droughts and locust outbreaks in recent decades (1). Consequently, livestock will likely have an even larger role in coming decades as compared to the present. Livestock and their products are among the key livelihoods many Senegalese producers are likely to shift toward as a result of climate change, and livestock may greatly assist producers to adapt to a changing climate in both northern and southern Senegal. Climate impacts, however, will differ greatly between the arid north and the more humid southern rangelands of Senegal.

In wetter rangelands (> 500 mm/yr) in the south of Senegal, significant changes in agricultural systems in coming decades may include growing more drought-tolerant and diversified rainfed crops than at present, increasing use of irrigation, and greater reliance on livestock and their products (2) among other livelihood sources. Several crops are projected to remain feasible for rainfed production in southern Senegal, including groundnut (of which Senegal is a top-five producer in Africa), pearl and finger millets, sorghum, and cassava (14). Under climate change, maize and other crops are projected to require significant adaptation of crop management practices (14) to be grown in future decades, especially more effective and efficient use of fertilizers and water (18). Livestock and their products are likely to take on a stronger emphasis in the household mix of livelihood sources in southern Senegal, which may seem counterintuitive since rangeland biomass and livestock productivity are projected to decline. The likelihood that southern Senegal rangelands will become drier by 2050 suggests greater future suitability of these areas for livestock relative to rainfed crops, and less severe rangeland degradation from livestock production (15) leading to potentially more sustainable rangeland livestock production. By providing manure and draft power to assist climate change adaptation through boosting crop yields (18), livestock help drive crop agriculture as well (19). For these reasons, the current importance of livestock to the larger agricultural sector and local and national economies (1) is set to expand in coming decades. Of course, as other livelihoods become available to rural residents, many could shift into new or emerging enterprises, ranging from small-scale poultry, to more commercialized agricultural value chains, to solar power generation, and beyond.

In contrast, in drier rangelands (< 500 mm/yr) in northern Senegal, no major shift in rainfall can be expected, although it is not exactly clear how rainfall will change, if at all. These rangelands appear likely to maintain the present production of biomass and livestock. No drastic transformation of agro-livestock systems is anticipated, and ongoing efforts to improve livestock production, crop yields, and their sustainability may be just as relevant in 2050 as today. Significantly, agricultural development programs and the use of improved management practices can continue on their present course toward sustainable intensification (1). Existing policies, extension, research, information systems, and other sectors that support livestock and agriculture in northern Senegal will likely be equally relevant, applicable, and strategic as at present. In addition, conservation areas in northern Senegal will likely retain their present ecological capacity to support wildlife populations and ecotourism. Projections for specific localities should not be used in calculations, recommendations, or otherwise. Rather, the average projection for the entire Sahelian Zone of northern Senegal (Table 1) is the best estimate.

Land, livestock, and policy options for productive and resilient rangelands

Adaptation to climate change at societal level in Senegal can benefit substantially from rangeland livestock production, and there are several strategic options for producers and for policymakers. Land management will be more important than ever, and practical strategies are needed, especially in pastoralist drylands and communal lands in farming zones. New options are emerging for management of communal grazing lands, which focus on building the capacity of local producer institutions to manage the land for mutual benefit. Building local institutions provides a means to achieve restoration, develop alternative incomes, and manage land, livestock, and crops more efficiently.

These approaches include community-based rangeland management (20), Participatory Rangeland Management (21), and communal grassland management in farming areas (22). Low-cost approaches for rangeland restoration are being developed (23,24), while simply monitoring for degradation can be a management and policy tool in certain contexts (25). Meanwhile, many rangeland landscapes are undergoing rapid and often unproductive land use changes—such as unsustainable temporary cropping of marginal grazing lands on poor soils, unsanctioned privatization of communal lands, and ill-advised forestry plantation (26). To prevent these and other negative outcomes, land use planning is critical for zoning land uses where most appropriate and sustainable (27,28). Further, a clear sense of access to land and resources for herders is key to the management of communal grazing lands, as is codified access in, for example, communal fisheries and forests. Clear and durable recognition of rights for communal use or communal ownership significantly enhances management and sustainability (29) and benefits the preservation and restoration of rangelands for sustained productivity. Stepwise intensification of rangeland livestock production under climate change will further benefit from policies and investments in support of information needs of producers, and the legal, financial, and infrastructural (livestock routes, abattoirs, markets, etc.) conditions that can accelerate rural development (1).

Livestock management can play significant roles in improving production efficiency and adaptation to climate change. Dual-purpose food-feed crops (30) and planted fodder can be crucial supports in times of poor rainfall, though they also rely on rainfall (or irrigation) and face challenges similar to rainfed crops. Like crops, private fodder plots can fragment rangelands into small areas, often diminishing natural resources and communal well-being (20). Veterinary care and surveillance for disease pathogens and vectors can limit livestock mortality and help detect outbreaks (31), and can be merged with rangeland management for joint improvement in One Health (32). Shifting livestock herd composition enables a better fit of livestock feed demand to available feed resources and management needs. Browsing livestock such as goats and camels largely prefer woody browse to grassy forages, making them more drought-resilient than grazers like cattle and sheep. Browsers can productively utilize excessive woody vegetation and promote recovery of grassy or mixed pastures, also controlling wildfire risk. Small ruminants (goats and sheep) are more drought-resilient than cattle, given their lighter feed and water needs, greater mobility, and lower risk of mortality, most especially for goats (33). Breeding of climate- and disease-adapted livestock is important, though breeders face challenges in anticipating changes in climate, disease risk, and production systems, including the feed base and veterinary services. Manure management techniques such as periodic movement of mobile livestock corrals (34) can fertilize the land and boost rangeland productivity (a technique long practiced by pastoralists in Africa), while efficient use of manure can support climate adaptation of crops (18). All of these options are equally relevant throughout northern and southern Senegal, although their implementation would normally differ.

On the other hand, direct control of stocking rates will not likely be the most useful tool for improving land and livestock management. Climate-induced aridification and declining stocking rates in southern Senegal, and existing aridity in northern Senegal, make the use of stocking rates at carrying capacity problematic. High stocking rates can reduce rangeland condition over the long term. However, stocking rates and rotations often have little effect on rangeland quality (35,36), and stocking rates are practically difficult to reduce in communal pastoralism for multiple reasons. In southern Senegal, loss of rainfall and biomass and more frequent droughts may cause stocking rates to decline and stabilize at a lower livestock density. Further reduction of stocking rates would likely be socially and economically unacceptable. Lower densities would limit economies of scale—in dairy, for example—and lessen fertilizer and draft power inputs to crop production. In northern Senegal, stocking rates may remain similar to the present. In more arid drylands, a major challenge for producers is to predict appropriate stocking rates in advance of a certain season, since rainfall varies wildly in arid lands (sometimes over short distances). An arid rangeland can be understocked one year; then overstocked as a drought hits the next; and then again understocked the following year due to mortality (37). If rainfall in the coming season cannot be reliably predicted at local scales, the ideal stocking rate is not predictable either. For these reasons, the United States Bureau of Land Management (BLM) is currently testing with a pilot group of private ranchers whether to alter or possibly end the use of carrying capacity in setting federal grazing permits for dry rangelands on federal lands (25).

Implications for mitigation of GHG emissions

Efforts to sequester carbon in rangeland soils, lands, or ecosystems in Senegal should proceed cautiously and with due diligence, as in any region of the world impacted heavily and negatively by climate change. In southern Senegal, strong constraints face carbon sequestration, while Sahelian rangelands in northern Senegal have stable though modest carbon storage potential. In fact, if current climate projections come to pass, wetter rangelands in southern Senegal are projected to lose carbon due to declines in rainfall, biomass production, soil organic carbon stocks, and total ecosystem carbon stocks. These losses of carbon are a direct threat to the feasibility of carbon storage in southern Senegal rangelands, a threat that may be exceptionally challenging to overcome. These strong trends indicate that many efforts to sequester carbon in rangeland soils, land, or ecosystems may struggle to successfully store carbon through the year 2050 in southern Senegal.

In northern Senegal, carbon storage in rangelands is technically feasible, and will likely remain feasible under climate change through 2050. Three main challenges face carbon storage in Sahelian rangelands. First, vegetation in deserts and other arid rangelands grows slowly because of little rainfall, meaning low and slow inputs of carbon to the ecosystem. Second, scientific prediction of carbon storage rates is frustrated by low effect size, high variance, long time periods to measure change in soils (up to 10 years), and the general absence of information describing rangeland management practices and their impacts on carbon stocks across major ecological and management gradients (13), most particularly in communal pastoralist systems. Technologies must be well calibrated to successfully predict the small amounts of carbon stored across large rangeland landscapes with volatile rainfall and often vague effects of management practices with numerically small marginal effects. These methodological constraints may ease as technology advances, yet presently much work remains on measuring the carbon storage potential of arid rangelands and demonstrating links to specific management practices. The final major challenge relates to communal pastoralist lands—land tenure policy formulation and implementation is an important precondition for productive, appropriate and ethical dedication of carbon revenues to designated beneficiaries in a durable legal framework.

On a more positive note, there are multiple alternatives to ecosystem carbon storage for reducing GHG emissions and emissions intensity in livestock systems. These options are viable across pastoralist rangelands, agro-pastoral areas, and mixed crop-livestock farming. Mitigation measures available for livestock include improved feeds and veterinary care to enhance production efficiency, manure management to reduce GHG emissions from manure and exploit this key fertilizer resource, and attention to emissions hotspots such as corrals and water bodies (38). Protecting surface water and using mobile corrals (34) would directly reduce GHG emissions. The mitigation benefits from these and most other viable approaches are poorly documented for the African continent (39), with communal pastoralism most poorly represented, and more empirical data are needed to accurately assess GHG emissions baselines and likely reductions.

Conclusion

Climate change impacts from shifting global weather patterns leading to changes in rainfall and aridity are likely to differ greatly between the wetter southern rangelands of Senegal, and the drier northern rangelands of the Sahel. The boundary of the Sahelian and Sudano-Sahelian Zones (~500 mm/yr) may be close to the dividing line between those areas that are relatively unaffected by climate change directly, and those areas affected strongly and negatively. Wetter southern rangelands (> 500 mm/yr) of Senegal may be likely to face strong reduction of rangeland biomass and livestock production, in addition to climate impacts on rainfed crops. Meanwhile, the drier Sahelian northern rangelands (< 500 mm/yr) may well maintain their current production of rangeland biomass, livestock, and crops, since no large negative changes in rainfall or aridity are expected.

Climate impacts on rangeland biomass production are likely to significantly reduce the long-term livestock production potential of wetter rangelands in southern Senegal. These impacts are alarming and reaffirm the need for feasible and effective adaptation of agricultural systems to climate change. However, if these areas do become more arid, rainfed cropping feasibility will also decline, and the potential sustainability of these areas for livestock production may improve. For these reasons, livestock will probably be among the more important options enabling rural residents and producers to diversify production and income streams under severe climate impacts. The forecast is vastly different for the drier northern rangelands of Senegal, where minor climate impacts are projected, and where existing agricultural and livestock production systems may be relatively uninterrupted. These projections do not include the impacts of increasingly frequent droughts and floods, nor do they account for good or poor land management leading to degradation or rehabilitation of rangelands.

The current importance of rangelands and livestock for economy, livelihoods, nutrition, and environmental goods seems set to increase in coming decades throughout Senegal. Livestock may significantly assist producers' ability to adapt, including indirectly through supporting climate adaptation of rainfed and irrigated cropping. Projected negative changes in the rangelands of southern Senegal, in terms of impacts on rangeland biomass, livestock, and crop production, can guide producers and policymakers to identify appropriate and strategic climate adaptation options. On the other hand, the absence of strong climate impacts projected for the drier northern rangelands of Senegal indicates that in the Sahel, current efforts toward sustainable intensification of crop and livestock production may largely proceed on their present course. Projected changes in rangeland productivity and agricultural and livestock systems can help guide the development of initiatives and management techniques to sustainably intensify rangelands and the larger agricultural sector, toward maintaining rural livelihoods and economy in Senegal in spite of ongoing climate change.

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