Agricultural Systems 192 (2021) 103203

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Research paper

A framework for assessing the effects of shock events on livestock and environment in sub-Saharan Africa: The COVID-19 pandemic in Northern Kenya

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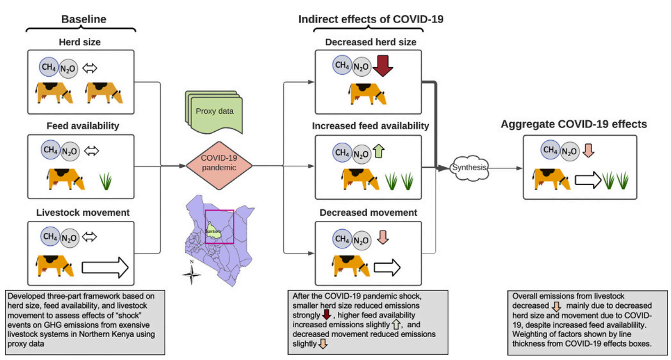
HIGHLIGHTS

- Develop framework based on 1) herd size, 2) feed availability, and 3) livestock movement to assess change in emissions
- Develop framework based on 1) herd size, 2) feed availability, and 3) livestock movement to assess change in emissions
- COVID-19 pandemic in Northern Kenya indirectly decreased herd size and animal movement, but feed availability was unaffected
- The pandemic indirectly decreased emissions from livestock in Northern Kenya, which was driven mainly by decreased herd size
- Our framework favored rapid evaluation GHG emissions from livestock and needs to be tested for other locations and years

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Dr Emma Stephens

Keywords:
Greenhouse gas emissions
Panel survey data
Crowd-sourced data
Pastoralism
Climate change
Herd size
Feed availability

ABSTRACT

CONTEXT: Livestock are the primary source of greenhouse gas (GHG) emissions from agriculture in most African countries, but there is a paucity of baseline data and monitoring of GHG emissions from livestock in Africa, particularly for extreme or shock events. The COVID-19 pandemic represents a novels shock to livestock systems and may result in indirect effects on livestock emissions and other Sustainable Development Goals (SDGs). Due to the pandemic in 2020, extensive pastoralist livestock systems in Northern Kenya were subjected to restrictions on movement, increased costs of transportation, and closure of livestock markets.
OBJECTIVE: The objective of this study was to assess the indirect effects of the COVID-19 pandemic on GHG emissions from livestock systems in Northern Kenya using proxy data and a three-part framework based on changes in 1) herd size, 2) feed availability, and 3) livestock movement.

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https://doi.org/10.1016/j.agsy.2021.103203
Received 2 January 2021; Received in revised form 31 May 2021; Accepted 9 June 2021
Available online 21 June 2021

METHODS: We evaluated changes in GHG emissions from livestock systems in Northern Kenya due to the COVID-19 pandemic based on proxy data from crowd-sourced market data, household panel surveys, and remote sensing data on Normalized Difference Vegetation Index (NDVI). Proxy data were obtained before the pandemic in 2019 and after the pandemic in 2020 to compare between years and evaluate the indirect effects of the pandemic and associated restrictions on livestock GHG emissions using the three-part framework.
RESULTS AND CONCLUSIONS: Overall GHG emissions from livestock in Northern Kenya have decreased due to the pandemic and this was largely driven by reductions in herd size. This reduction in GHG emissions occurred despite an increase in GHG emissions from livestock associated with higher feed availability. Decreased livestock movement due to the pandemic contributed to reductions in GHG emissions from livestock, but such reductions were likely to be small due to limited need for livestock to travel longer distances under the prevailing conditions of high feed availability.
SIGNIFICANCE: This research shows that assessments of changes in GHG emissions from livestock systems due to shock events can be conducted successfully based on proxy data and the three-part framework developed here. We found that shock events, such as the COVID-19 pandemic, may lead to unexpected results with respect to the direction and magnitude of changes in livestock emissions depending on contextual factors and environmental conditions. Thus, we call for more spatially explicit and continued data collection to assess and monitor the consequences of shock events on GHG emissions from livestock and related SDGs in Africa.

1. Introduction

The COVID-19 pandemic is expected to have widespread and negative impacts on multiple Sustainable Development Goals (SDGs) related to agriculture in sub-Saharan Africa (SSA). The associated changes in socio-economic circumstances may indirectly affect agricultural productivity through disruptions in access to resources, particularly due to movement restrictions and reductions in access to markets for farm inputs and labor. A preliminary body of work has demonstrated that deleterious effects of the COVID-19 pandemic on agricultural systems in SSA could exacerbate poverty (SDG1), food insecurity (SDG2), and human health and well-being (SDG3) (Arndt et al., 2020; Devereux et al., 2020; Griffith et al., 2020; Mhlanga and Ndhlovu, 2020), whereas a renewed focus on One Health in Africa could lead to long-term improvements in human and livestock health (Fasina and Fasanmi, 2020).

While the small currently available body of research has focused on food security and household income, the potential impacts of COVID-19 on biophysical aspects of agricultural productivity and livestock systems have received comparatively little attention (Griffith et al., 2020). There has been some research regarding the impact of COVID-19 on the environment and climate change at the global scale (SDG 15 and SDG 13, respectively) (Friedlingstein et al., 2020; Le Quéré et al., 2020; Zhang et al., 2020). Yet, no assessments of the potential for interactions between the effects of the pandemic on agriculture vis-a-vis the environment and greenhouse gas (GHG) emissions in SSA have been conducted.

Livestock are an important source of livelihoods and serve multiple functions within agricultural systems in SSA, which have been shown to contribute positively to several SDGs (Robinson et al., 2011; Truebswasser and Flintan, 2018; Domínguez Salas et al., 2019; Enahoro et al., 2019). Besides this positive contribution, agriculture is also responsible for a large proportion of anthropogenic GHG emissions and accounts for up to 60% of total GHG emissions at the national scale in many African countries (Niang et al., 2014; Thornton and Herrero, 2015). Livestock are the primary source of GHGs from agriculture at the continental scale, with CH_4 from enteric fermentation accounting for 47% of agricultural GHG emissions, while N_2O emissions from manure are estimated to account for an additional 5–17% of cumulative GHGs from agriculture (Tubiello et al., 2014; Valentini et al., 2014; Butterbach-Bahl et al., 2020).

1.1. Background and study area

Livestock production in extensive pastoralist systems represents the dominant land use and source of livelihoods and economic activity in arid and semi-arid lands (ASALs) in East Africa (Robinson and Berkes, 2010; Mburu et al., 2017). Extensive livestock systems in the ASALs in East Africa are characterized by grazing and browsing of multiple livestock species (i.e. cattle, goats, sheep, camels), as well as high levels of mobility and movement of animals to exploit heterogeneous and patchy distribution of resources across the landscape (Robinson, 2009). Livestock systems in the region are fluid and often involve the movement of people and animals across local, national, and international boundaries (Oba, 2013; Jensen et al., 2017). Pastoralist households are heavily dependent on livestock for income and access to other services, with an estimated average of 70% of income derived from livestock-related activities in the region (Jensen et al., 2016).

ASALs in East Africa are subject to frequent droughts and other "shock" events (e.g., disease outbreaks, export bans) (Bonnet et al., 2001; Pratt et al., 2004; Ahmed et al., 2019) that can result in substantial losses of livestock (>50% in many instances) and exacerbate food and economic insecurity (Jaetzold and Schmidt, 1983; Peyre et al., 2015). The COVID-19 pandemic likely represents another major shock – previously not identified – to extensive livestock systems in these areas because countries in East Africa have closed livestock markets and restricted the movement of people across national and international boundaries for a consecutive period of >3 months in 2020 (Griffith et al., 2020). Extensive pastoralist livestock production in the region may be affected by COVID-19 related restrictions on movement because of the dependence of these systems on seasonal migration to obtain access to forage and water for livestock. Pastoral livelihoods may also be vulnerable to COVID-19 related changes in access to markets and in "terms of trade" for livestock products (Jensen et al., 2017).

Shock events are likely to indirectly affect GHG emissions from livestock in ASALs due to losses of livestock that reduce herd size. In addition, shock events may indirectly impact livestock GHG emissions through changes in the quantity and quality of available feed, as well as by altering patterns of livestock movement and mobility. However, the effects of major shock events on livestock GHG emissions have not been explored in detail and the magnitude and direction of these effects remain uncertain because there has been no practical way to obtain the requisite data. Thus, there is a need to develop such data collection methods and to examine the critical nexus between shock events, i.e., the COVID-19 pandemic, livestock, and the environment (i.e., GHG emissions) at the local to regional scale in the African context.

Here we focus on extensive pastoralist systems in Northern Kenya as a representative test case for evaluating the impact of the COVID-19 pandemic on livestock GHG emissions for ASALs in East Africa. Most of Northern Kenya consists of ASALs where annual precipitation ranges from <250 to 500 mm with a coefficient of variation >25% in many locations (Hengsdijk et al., 2014). Precipitation in the region follows a bimodal distribution, with a long rainy season occurring from March to May and a short rainy season from October to December (Herrmann and Mohr, 2011). In response to the COVID-19 pandemic, the Government of

Kenya implemented restrictions on movement of people between administrative units (e.g., counties) throughout the country in 2020, as well as limiting transit of people and animals across international borders. Movement restrictions between counties and across international borders in Northern Kenya were enforced from the end of March until July 2020, when restrictions across counties and some international borders were lifted. Restrictions on vehicle capacity (<50%) were in effect for much of this time period and increased costs of transportation for people and livestock. In Northern Kenya, large formal intermediate markets for livestock were closed in late March 2020 for a period of at least one month before being deemed essential and reopening around the beginning of May 2020. However, some decisions on reopening of markets were undertaken at the county level and the process was reportedly somewhat haphazard, since some local feeder markets remained closed or re-opened only sporadically (Chelanga, pers. comm.).

1.2. Developing a framework for assessing the effects of shock events on GHG emissions from livestock

We have developed a framework that can be used broadly to assess the impacts of shock events, such as the COVID-19 pandemic, on GHG emissions from livestock at the local to regional scale in SSA. Based on previous work estimating GHG emissions from livestock for other locations in East Africa (Goopy et al., 2018; Ndung'u et al., 2018), we propose a three-part framework for assessing the impact of shock events on GHG emissions from livestock based on: 1) changes in herd size or the total number of animals in the region; 2) changes in availability of feed for livestock; 3) changes in livestock mobility (Fig. 1).

(1) Herd size is a primary determinant for GHG emissions from livestock (enteric CH_4) and manure (CH_4 and N_2O) because more animals on the land results in higher cumulative GHGs from livestock at all scales. Shock events (e.g. droughts, disease outbreaks, export bans) can lead to substantial losses of livestock and reductions in herd size, which leads to changes in cumulative and per-head livestock GHG emissions.

(2) Feed availability impacts GHG emissions from livestock via the amount of feed biomass consumed and the efficiency at which a given feed is digested and utilized by animals (Herrero et al., 2008, 2013). Larger quantities of feed consumed generally increase emissions due to higher throughput of feed biomass through livestock digestive tracts. Increased feed digestion leads to greater potential for enteric CH_4 production and causes increases in CH_4 and N_2O emissions due to higher excreta output (Ali et al., 2019; Goopy et al., 2020). Shock events may reduce the availability of feed due to poor vegetation condition, or by preventing animals from accessing feed resources due to restrictions on livestock movement (Megersa et al., 2014; Vrieling et al., 2016).

(3) Changes in movement or mobility of livestock affects GHG emissions indirectly through energy expenditure, which results in changes in feed consumed and thus also GHG emissions (Goopy et al., 2018). Movement may also impact the distribution and concentration of livestock manure, which previous studies have shown to impact GHG emissions (Augustine et al., 2003; Porensky and Veblen, 2015; Butterbach-Bahl et al., 2020). Shock events are likely to alter movement patterns by increasing the distances required to obtain feed resources, or through market closures and restrictions on livestock movement (Butt, 2010).

We have used this framework to qualitatively assess the potential impact of the COVID-19 pandemic on livestock and, indirectly, GHG emissions in Northern Kenya using proxy data (crowd-sourced market data, household socio-economic survey data, and remote sensing vegetation data). Specifically, we use the framework and data to evaluate the following hypotheses:

1. Herd size will decrease as a result of the COVID-19 pandemic.
2. Feed availability will decrease as a result of the COVID-19 pandemic.
3. Livestock movement will decrease as a result of the COVID-19 pandemic.

2. Materials & methods

2.1. Crowd-sourced market data (KAZNET)

Crowd-sourced data were collected from livestock markets in Northern Kenya using the KAZNET micro-tasking platform. The KAZNET platform was developed by the International Livestock Research

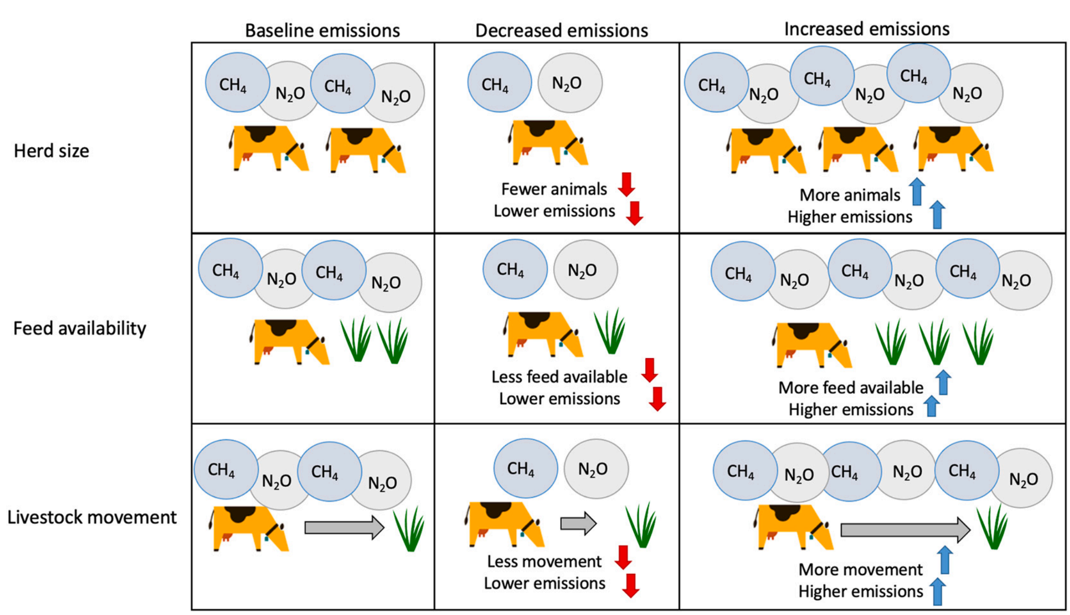

Fig. 1. Schematic diagram of a three-part framework for assessing greenhouse gas (GHG) emissions from livestock based on herd size, feed availability, and livestock movement as developed in this study.

Institute as a mobile phone application using ONA's Open Data Kit software (https://ona.io) to monitor market conditions and prices for livestock products in Northern Kenya (Banerjee, 2019; ILRI, 2019). KAZNET data is generated by reports from users, who are mainly financial intermediaries and other actors operating in livestock markets in Northern Kenya. We used KAZNET to collect data for quantitative and qualitative variables from 76 individual users in ten formal, intermediate livestock markets throughout Northern Kenya (Fig. 2) from 11 November 2019 to 1 September 2020. We collected data on variables related to volumes of livestock passing through markets as a proxy for changes in herd size, feed availability in the vicinity of markets, and variables related to livestock movement (please refer to Supporting Table 1 for a detailed list of the collected variables). Subsequently, weekly means or weekly response frequencies were used to create a time-series of all variables for the entire study period. We assumed that market closures due to COVID-19 restrictions went into effect in the third week of March 2020 and that re-opening of formal intermediate markets occurred in the first week of May 2020. Subsequently, we divided the time series into three time periods (pre-, mid-, and post-market closure) and compared means for variables during each of the time periods.

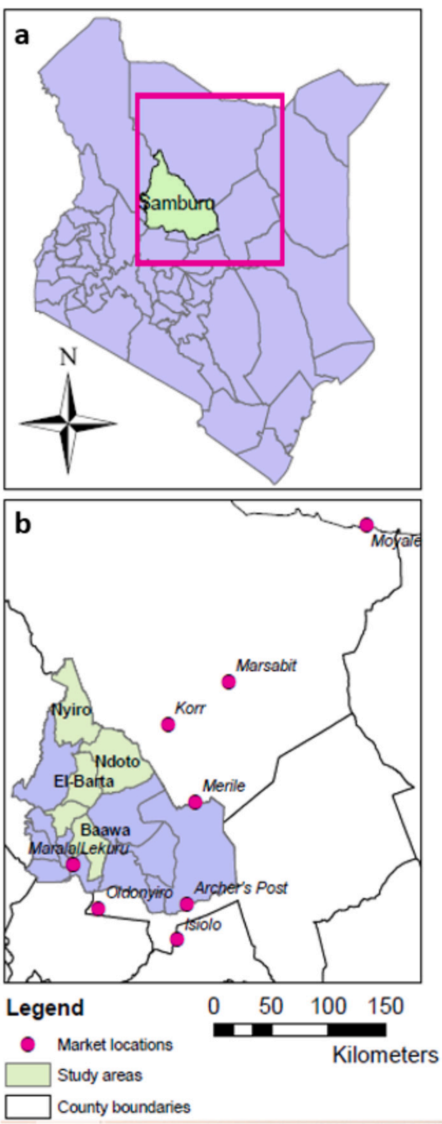

Fig. 2. Map of study area with Panel A showing the location of Samburu County in Northern Kenya, where the panel survey was conducted (highlighted in green). Panel B is a zoom to show the wards in Samburu County where household panel surveys were conducted (highlighted in green) and locations and names of formal livestock markets in Northern Kenya, where crowd-sourced market data were obtained (pink dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Panel survey data

We collected socio-economic data from household panel surveys of 404 pastoralist households in Samburu County between February 2018 and August 2020 (Fig. 2a). Details on the sampling and tools used for collecting the panel survey data can be found in Alulu et al. (2020). Characteristics of surveyed households can be found in Supporting Table 2. To assess the impact of the COVID-19 pandemic on changes in herd size in Samburu, we compared reported initial livestock holdings and livestock transactions from surveyed households in 2019 (baseline) and 2020 (pandemic). In the household surveys, baseline data on initial livestock holdings were collected for each livestock species (camels, cattle, goats, sheep) for households in February 2018 and February 2020; for the purpose of this study we used livestock holdings in February 2018 and February 2020 to obtain an interpolated estimate of livestock holdings in February 2019. Changes in herd size during 2019 and 2020 were then calculated from initial livestock holdings using data on the number of livestock transactions (births, deaths, purchases, sales, slaughter) in each year from household surveys conducted in August 2019 and August 2020.

Additionally, data regarding the specific effects of the COVID-19 pandemic on changes in herd composition, feed availability, feed cost, and livestock movement, as well as the impact of movement restrictions were collected in August 2020. Although it was not possible to directly compare data obtained for these variables in previous years, we assumed that the August 2020 data served as reasonably good indicators of COVID-19 impacts on these variables because respondents were asked specifically to evaluate the impact of the pandemic.

2.3. Remote sensing data

Time series of Moderate Resolution Imaging Spectroradiometer (MODIS) 16-days maximum-value composite Normalized Different Vegetation Index (NDVI) imagery (product MYD13Q1) were used as a proxy for vegetation biomass production in the areas surrounding the ten formal intermediate livestock markets in the crowd-sourced dataset. NDVI is a common proxy for photosynthetic activity in remotely sensed vegetation and is therefore a strong indicator of vegetation biomass (Weier and Herring, 2000). Previous studies on NDVI in Northern Kenya have demonstrated a strong relationship between NDVI, as a predictor of feed availability from natural vegetation, and livestock mortality (Chantarat et al., 2013).

NDVI values were averaged for a 10 km $\times$ 10 km buffer surrounding each of the ten formal intermediate livestock markets in Northern Kenya. To exclude built-up and unvegetated areas, only areas within the 10 $\times$ 10 km buffer that contained a meaningful area of forage or grazing land were included in the NDVI calculations. Then, for every 16-day period, the five-year average NDVI value for 2015–2020 was calculated as a reference with which to compare the 2019–2020 study period. Subsequently, NDVI for the study period and five-year NDVI values for the ten markets were averaged together to calculate aggregated time series of NDVI and five-year NDVI as proxies for potential feed availability.

3. Results

3.1. Assessing changes in herd size

3.1.1. Crowd-sourced data on herd size from formal intermediate markets

Patterns for livestock volumes, which are a strong indicator of livestock sales and market activity, were similar for all four livestock species averaged across ten formal intermediate markets in Northern Kenya for the November 2019 to September 2020 time period (Fig. 3). Reported volumes in head per day for all four species showed considerable variability between markets, with standard deviation values higher than the means for most species and time periods. Weekly averages were highest from November 2019–March 2020. This was followed by a steep decline and period of little activity following the closure of formal intermediate markets due to COVID-19 restrictions at the end of March 2020. Reported livestock volumes subsequently recovered following the re-opening of formal intermediate markets starting around May 2020 and remained somewhat lower than prior to the start of the COVID-19 pandemic across all four species.

3.1.2. Data on herd size from panel surveys of pastoralist households

Panel survey data collected among pastoralist households in Samburu County showed an increase in nearly all transactions for 2020 compared to the same time period in 2019 (Supporting Fig. 1), with the exception of births and deaths (in the absence of data on births and deaths for 2020, we assumed that these were similar as a proportion of initial herd size to those in 2019). The number of livestock leaving the herd through deaths, slaughter, and sales was larger than the number of animals entering through births and purchases in both years, which resulted in a negative net change in livestock numbers among surveyed households in both 2019 and 2020 (Fig. 4). However, the net negative balance was much larger in 2020 compared to 2019 across all species. Data collected in August 2020 on the direct effects of COVID-19 on herd composition among surveyed households showed either no change or a decrease in livestock numbers for all species (Fig. 5).

3.2. Assessing changes in feed availability

3.2.1. NDVI data on vegetation condition and potential feed availability

Mean NDVI data across all ten markets indicated that vegetation condition and feed availability for livestock grazing and browsing varied at the regional scale with the commonly observed seasonal pattern (low feed availability in the dry season, high feed availability in the rainy season) for 2019 and 2020 (Fig. 6). Compared to the five-year mean, NDVI was somewhat low in the long rainy season (March – May) and long dry season (June – September) in 2019, indicating below-average vegetation condition and feed availability during this time. In contrast, the short rainy season starting in October 2019 was much longer and extended into January 2020, which sustained above-average vegetation condition and potential feed available for livestock until the beginning of the long rainy season in March 2020. This was indicated by the above-average NDVI values from October 2019 to March 2020. After a slight drop, NDVI increased again in March 2020 in association with the long rainy season and reached a peak in May 2020, before declining again with the cessation of the long rains in June 2020. Nevertheless, NDVI values and vegetation biomass remained above average during both the long rainy season and long dry season (June – September) in 2020.

3.2.2. Crowd-sourced data on feed availability from formal intermediate markets

Crowd-sourced reports on weekly levels of forage availability in Northern Kenya appeared to be relatively unaffected by changes associated with the lockdown and movement restrictions in Kenya, and instead followed seasonal trends as similarly shown by NDVI data. Forage availability was most frequently characterized as "very plentiful" from early December 2019 until mid-February 2020 (Fig. 7). The most frequently reported weekly forage status in the time period coinciding with the lockdown and intermediate market closures (i.e., between mid-

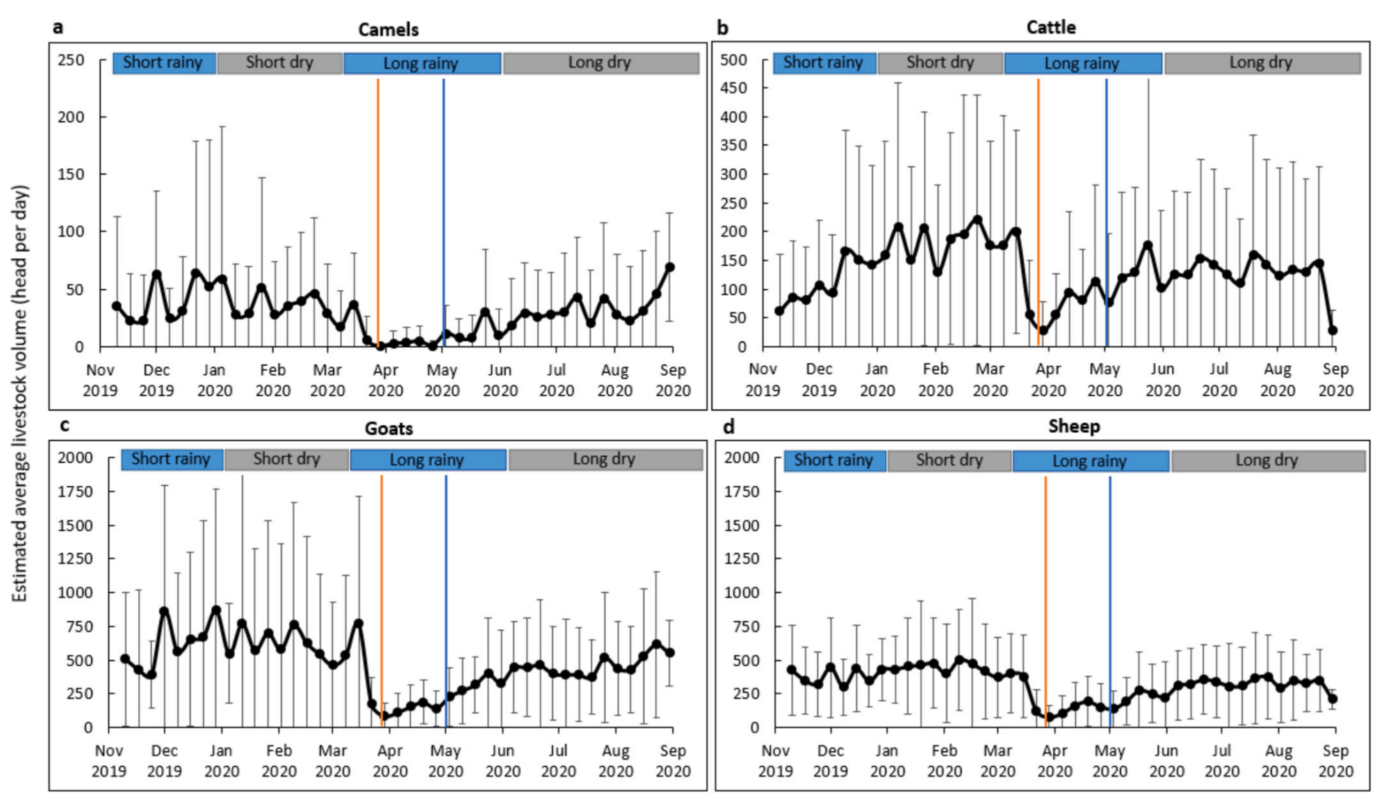

Fig. 3. Estimated weekly mean livestock volumes (a camels, b cattle, c goats, d sheep) across ten major livestock markets in Northern Kenya based on crowd-sourced data. Orange lines show start of movement restrictions and livestock market closures. Blue lines indicate approximate date of reopening of markets. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

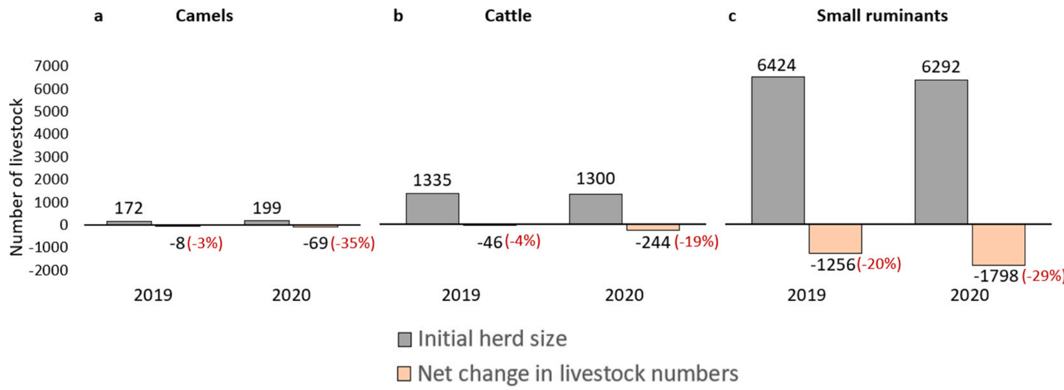

Fig. 4. Initial herd size (gray bars) and net change (%) in livestock numbers (red bars) estimated for 2019 and 2020 from panel survey data for 404 pastoralist households in Samburu County, Kenya. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

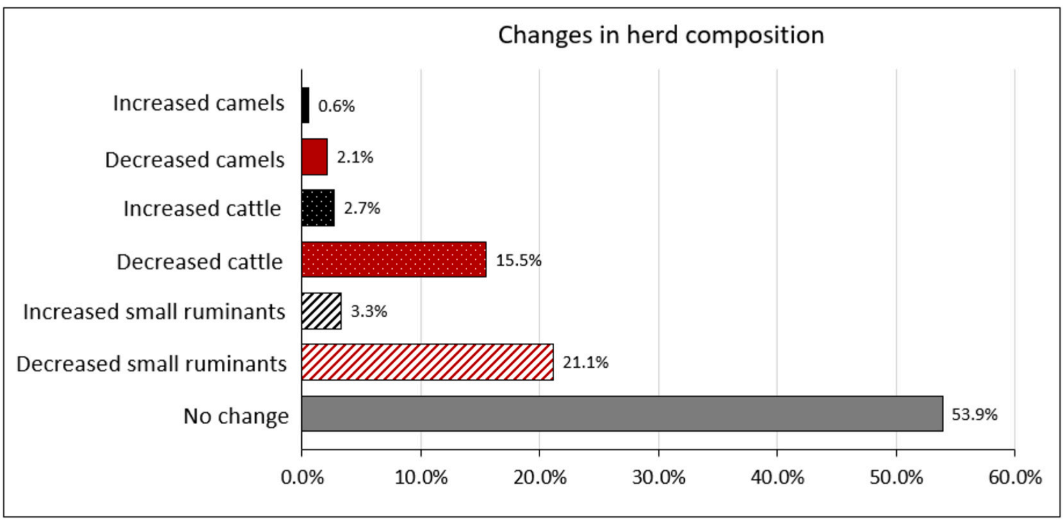

Fig. 5. Changes in herd composition reported in panel surveys conducted in 404 households in Samburu County, Kenya in 2020.

February and early May 2020) was "available", followed by "very plentiful", indicating a slight drop in forage availability due to a decrease in precipitation during the short dry season in 2020. Subsequently, weekly forage status was primarily described as "very plentiful" or "available" from May 2020 onwards, coinciding with the long rainy season. The proportion of responses indicating that forage was either "somewhat scarce" or "very scarce" exceeded 30% in only three weeks in the entire 44 week time-series, and did not ostensibly increase during the lockdown from late March to early May.

3.2.3. Data on feed availability from panel surveys of pastoralist households

Panel survey data on feed availability collected in August 2020 largely corroborated high levels of feed availability as previously observed from NDVI and crowd-sourced data (Fig. 8). The majority of households in the panel survey reported no change in availability of feed for livestock grazing and browsing due to COVID-19 and associated restrictions (84%), whereas approximately equal percentages indicated that feed availability had either increased or decreased as a result. A majority of households indicated that there had been no changes in the availability of purchased feed in 2020, but the percentage reporting a decrease (11%) was more than double the percentage reporting an increase (4%) (Supporting Fig. 2a). Similarly, most households reported either no change in the types of feed for livestock due to the pandemic, or reported increases and decreases for a given type of feed in approximately equal numbers (Supporting Fig. 2b).

3.3. Assessing changes in livestock movement

3.3.1. Crowd-sourced data on livestock movement from formal intermediate markets

Reported distances travelled to formal intermediate markets (Fig. 9) increased during the 2019–2020 time period, while distances to grazing areas and waterpoints were relatively stable, which was in agreement with reported high in-situ feed availability and precipitation (Supporting Fig. 3a). Reported distances to reach markets suggest that a majority of households travelled further to reach markets due the pandemic, since the most common characterization of distances to markets was "somewhat far" (43.9%) or "very far" (10.6%) relative to distances before the pandemic, with an additional 32% reported no change in distance to markets. The distance of livestock grazing areas from conflict zones was greater during the long rainy season in 2020, and this distance remained relatively large throughout the time series. This corroborates that livestock feed was abundant in-situ and there was limited need for pastoralists to risk travel to conflict zones to obtain resources (Supporting Fig. 3b). The decrease in distance of grazing areas from conflict zones in September 2020, at the end of the long dry seasons, indicates that feed resources may have become somewhat scarcer at this time.

3.3.2. Data on livestock movement from panel surveys of pastoralist households

Most households questioned in the panel surveys in Samburu (50%) indicated that there had been no change in livestock movement due to

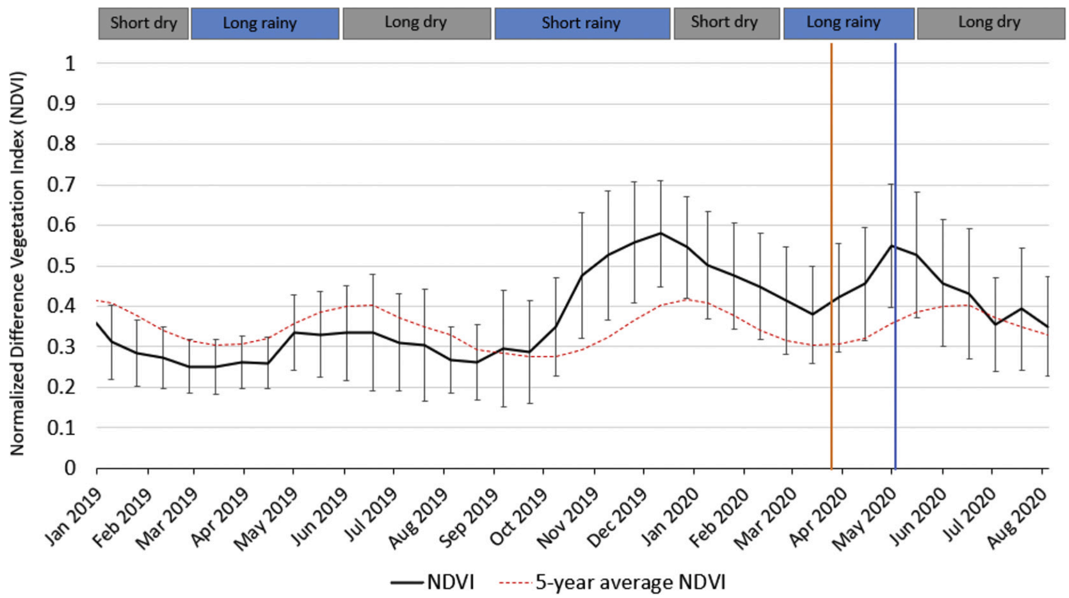

Fig. 6. Time series of biweekly values of Normalized Difference Vegetation Index (NDVI) values for study period (2019–2020) and five-year average NDVI values averaged across ten markets in Northern Kenya. The black line shows raw NDVI value over time from January 2019 to August 2020 for 10 km × 10 km areas surrounding the ten markets. The dashed red line shows the 2015–2019 mean NDVI for 10 km × 10 km areas surrounding the ten markets. The vertical orange line shows start of movement restrictions and livestock market closures. The vertical blue line indicates approximate date of reopening of markets. The typical pattern of annual seasonality in Northern Kenya is shown in blue and gray boxes at the top of the plot. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

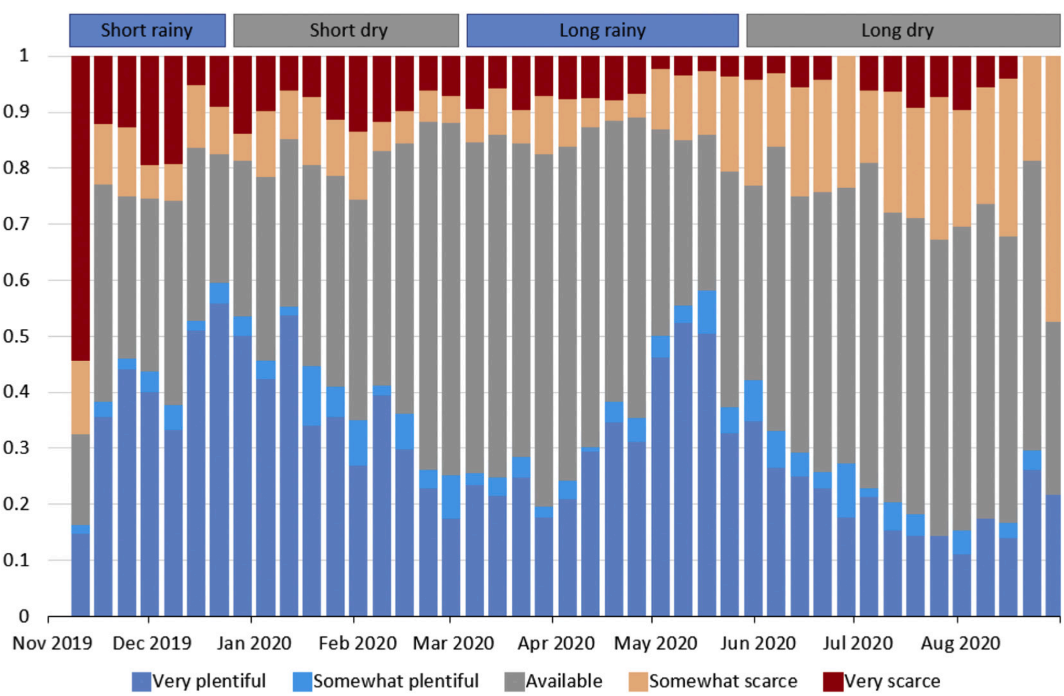

Fig. 7. Time series of proportional frequency of responses for reported livestock feed availability from crowd-sourced data for ten formal markets in Northern Kenya.

COVID-19 (Fig. 10a), while 31% of households indicated that movement had decreased and 19% reported increases in movement. The reasons for changes in movement of livestock included: 1) changes in distance moved, 2) changes in frequency of movement, and 3) changes due to conflict. Only a minority of households reported an effect of government-mandated restrictions on movement (Fig. 10b). A total of 37% of households reported that restrictions on movement had impacted livestock movement in some way, with these impacts mainly occurring between Samburu and adjacent counties (22%) or locally within Samburu County (15%). Restrictions on movement of people and livestock across international borders appear to have had minimal effects.

4. Discussion

4.1. Assessing changes in herd size and GHG emissions from livestock

Data from the household panel surveys suggest that herd size for

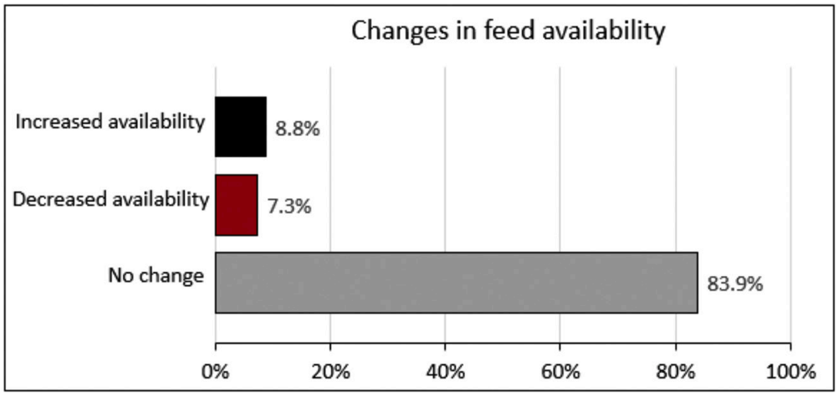

Fig. 8. Reported changes in livestock feed availability and feed types due to the COVID-19 pandemic from panel survey data in Samburu County, Northern Kenya.

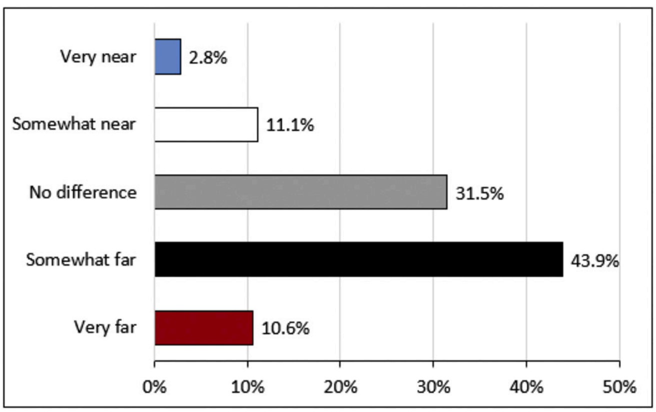

Fig. 9. Changes in relative distances travelled to reach formal livestock markets during movement restrictions due to the COVID-19 pandemic from crowd-sourced market data in Northern Kenya.

major livestock species and the resultant GHG emissions have decreased in Northern Kenya because of the COVID-19 pandemic and associated changes. Reductions in herd size ranged from −19 to −35% of estimated initial herd size depending on species in 2020 and were comparable to average losses attributable to drought previously observed in Northern Kenya, which are estimated to account for ~47% of losses of livestock among pastoralist households in the region (Jensen et al., 2016). Overall, reductions in herd size imply that GHG emissions from livestock in the region may be decreasing somewhat due to COVID-19.

Reductions in herd size occurred despite high feed availability and lower volumes of livestock passing through large, formal intermediate markets. These reductions in herd size likely took place through informal markets or directly between households, which may not be detected in the crowd-sourced data from formal intermediate markets. The pattern of reduced activity in formal intermediate markets is consistent with previous research showing that other shock events do not necessarily result in increased activity in formal intermediate markets, even when there are large losses of livestock (Pratt et al., 2004; Little et al., 2014).

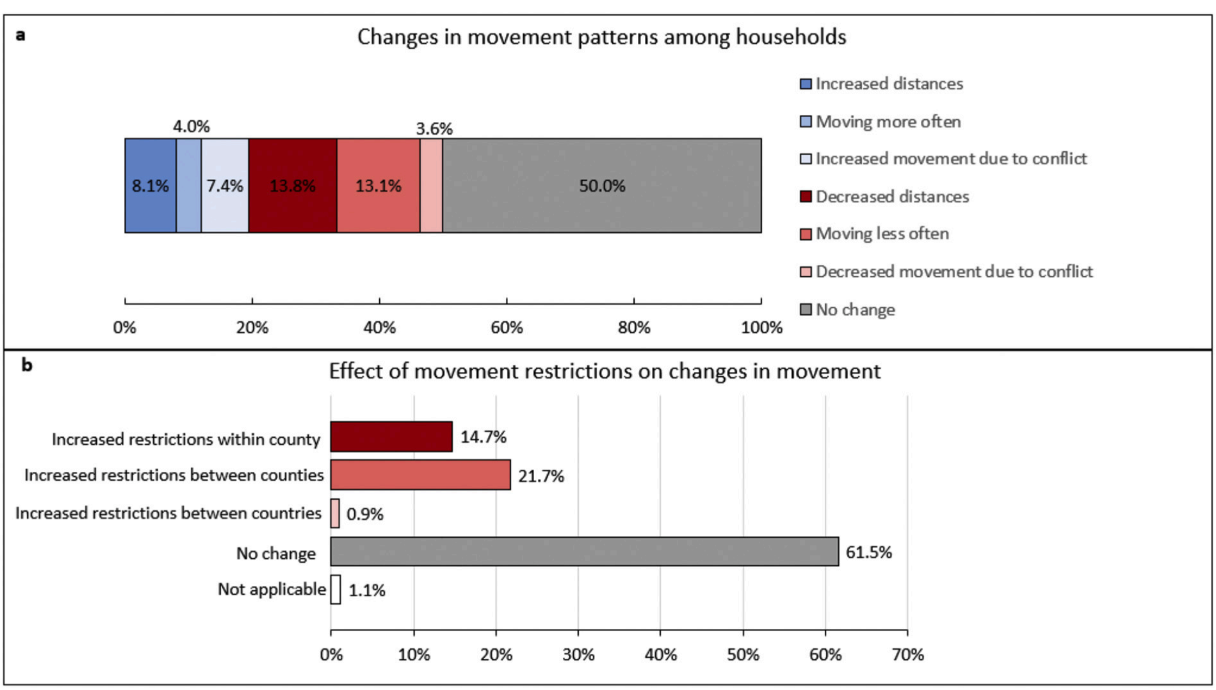

Fig. 10. Effect of COVID-19 restrictions on movement reported in panel survey data in Samburu County, Kenya. Panel a shows changes in "magnitude of distance moved", "frequency of movement", and "movement due to conflict". Panel b shows the reported impact of restrictions on livestock movement across administrative boundaries.

Household data may therefore be a more reliable indicator of changes in herd size due to shocks compared to market activity because they capture transactions within households and through informal markets that crowd-sourced data from formal intermediate markets fail to detect. Crowd-sourced data on the prevalence of transactions in informal markets did suggest that a large proportion of livestock was passing through informal markets in lieu of formal markets (Supporting Fig. 4). Households in the panel survey reported that livestock sales were taking place closer to homesteads during the pandemic, and were thus more likely to occur through informal channels. This change is likely attributable in part to the closure of formal feeder markets and increased costs of transportation associated with COVID-19 restrictions, but also to changes in behavior to avoid direct exposure and infection with COVID-19. This is consistent with anecdotal accounts of pastoralists in Northern Kenya resorting to informal channels following market closures and other COVID-19 restrictions (Chelanga and Banerjee, pers. comm.; Mercy Corps, 2020). Previous research has demonstrated that a large proportion of sales by pastoralists occur through informal channels, regardless of circumstances, though the exact volume of livestock is uncertain (McPeak, 2006; Little et al., 2015).

These results indicate more generally that large reductions in herd size in extensive livestock systems in East Africa may occur through informal channels. Additional research and data on reductions from the overall herd passing through informal markets and among households in the region is required to reduce uncertainty in estimating changes in livestock numbers and GHG emissions due to shock events. More generally, there is a paucity of data on the total livestock population in the region, creating large uncertainty in GHG budgets and rendering the estimation of effects of shock events on herd size and emissions difficult. Baseline data on herd size at the regional scale is therefore required to accurately monitor changes in livestock numbers and GHG emissions from livestock due to shock events.

4.2. *Assessing changes in feed availability and GHG emissions from livestock*

Feed availability appears to have been largely decoupled from changes related to COVID-19 in 2020 and was more closely associated with seasonal variation in precipitation and vegetation condition. The short rainy season in Northern Kenya was especially long and abundant in 2019 and extended into 2020 (Wainwright et al., 2020), which resulted in above-average vegetation conditions, even during the following short dry season in early 2020. Irrespective of changes in herd size, greater feed availability is likely to have increased absolute GHG emissions from livestock in Northern Kenya because increased digestive throughput of feed by ruminant (i.e., cattle, sheep, goats) and pseudo-ruminant (i.e., camels) livestock facilitates greater enteric CH_4 emissions and manure production.

The need for pastoralists to move or migrate to access feed and resources was likely minimal in 2020 due to high in-situ feed availability (see subsequent section on livestock movement). However, feed availability and livestock movement are often strongly correlated, since drier conditions tend to result in lower feed availability in-situ and thus increased distances travelled to reach feed resources. If drier conditions had prevailed in Northern Kenya in 2020, as is predicted for the long rainy season (March–May) in 2021 due to strong La Niña conditions (Funk, 2020), it is possible that there could be interactions between feed availability, GHG emissions, and COVID-19 restrictions. Government-mandated restrictions on movement could disrupt the long-distance migration and tracking patterns employed by pastoralists to obtain resources under drier conditions (Niamir-Fuller, 2001; Butt, 2010). Such conditions would also have likely resulted in larger reductions in herd size through death or de-stocking, causing further reductions in GHG emissions from livestock (Devereux and Tibbo, 2013). Therefore, it is important to treat the effects of feed availability on GHG emissions from livestock reported here with caution, and emphasizes the need for continuous monitoring of the feed availability in Northern Kenya and elsewhere in the region.

4.3. *Assessing changes in movement and GHG emissions from livestock*

The overall results indicate that livestock movement and thus GHG emissions may have decreased slightly due to indirect socio-economic changes associated with the COVID-19 pandemic. This small potential decrease in GHG emissions from livestock relative to baseline appears to be driven mainly by a sharp increase in livestock sales occurring locally, thus negating long-distance travel to reach formal intermediate livestock markets. Household survey data indicated either no change or a decrease in livestock movement, which are probably attributable to smaller distances travelled to sell animals locally. By contrast, the crowd-soured market data indicated that distance travelled to reach markets had increased, but this is primarily true for livestock being sold in the large intermediate markets on which the crowd-sourced data is based. As with the increase in sales locally, increased distances to reach formal intermediate markets are likely due to closure of local feeder markets, since livestock that are not sold locally must now travel longer distances to reach formal intermediate markets. The crowd-sourced data also support the notion that more sales appear to be occurring through local, informal channels, such as neighbors, local butchers, local traders and brokers (Supporting Fig. 5).

However, livestock movement is likely to be strongly correlated and entangled with feed availability and consumption. If there is sufficient feed and livestock movement requirements are limited, total GHG emissions should be higher due to increased consumption, despite the reduced movement. Under drier conditions with limited and patchily available feed resources, livestock may move over longer distances or more frequently, thus increasing energy expenditure, but absolute emissions will be low because of the relatively low feed consumption by livestock.

5. Summary and conclusions

We found that the three-part framework based on herd size, feed availability, and livestock movement was useful in assessing potential changes in GHG emissions from livestock due to the COVID-19 pandemic using proxy data in Northern Kenya. The direction of the response in terms of GHG emissions from livestock differed depending on the component of the framework evaluated – reductions in herd size and decreased livestock movement point toward a decrease in absolute emissions, whereas increased feed availability leads to increases in GHG emissions. Taken together, we conclude that total, absolute GHG emissions have likely decreased because of the importance of herd size relative to the other components (see Table 1 for matrix of scenarios with change in direction and magnitude of emissions as well as likelihoods for different scenarios based on the framework).

Under the specific circumstances of 2020, the effect of reduced herd size and decreased movement on lower emissions was slightly offset by enhanced GHG emissions from high feed availability. Due to unusually high precipitation and in-situ feed availability from the end of 2019 through 2020, it is unlikely that feed availability would be a limiting factor on GHG emissions even if herd size remained the same or increased. Relatedly, decreased emissions associated with reduced livestock movement are likely to have been minimal due to the relatively low baseline movement requirements associated with higher feed availability.

Nevertheless, the COVID-19 pandemic and associated socio-economic changes are likely to have accelerated long-term trends of inequality and sedentarization in Northern Kenya and ASALs in East Africa (Griffith et al., 2020; Mercy Corps, 2020), with implications for GHG emissions. Low-income pastoralist households may be forced to sell off livestock assets to meet their immediate financial needs as a result of the pandemic, increasing inequality and accelerating sedentarization

Table 1
Matrix of scenarios for herd size, feed availability, and livestock movement in Northern Kenya with associated direction and magnitude of changes in GHG emissions for each scenario. Positive changes in direction are indicated by " + ", whereas negative changes are indicated by " – ". Magnitude of expected change is indicated by quantity of each symbol displayed. Likelihood of each scenario is rated from "Low" to "High" based on subjective assessment.

Herd size	Feed availability	Movement	Direction and magnitude of emissions change	Likelihood of scenario
–	–	–	- - -	Medium to High
–	–	+	- -	Low to Medium
–	+	–	- -	Medium to High
–	+	+	–	Low to Medium
+	–	–	+	Medium
+	–	+	++	Low
+	+	–	++	Medium
+	+	+	+++	Low

near towns as households relocate in search of alternative income sources or exit from pastoralism entirely (Aklilu and Catley, 2013; Fratkin, 2013). Sedentarization of pastoralist households reduces livestock mobility, which may in turn reduce the quality and quantity of feed available for livestock. Sedentarization often initiates a vicious cycle because immobility results in overgrazing and land degradation around settlements, further reducing feed quality and availability (Weber and Horst, 2011; Groom and Western, 2013). Increased sedentarization as a coping strategy due to the pandemic may therefore reduce future GHG emissions from low-income pastoralist households because of reduced movement and decreased quantity and quality of feed resources, while land degradation around settlements impairs rangeland biomass production and capacity of these ecosystems to store carbon. Additionally, sedentary households may shift to more resilient and opportunistic livestock species, such as sheep and goats, which have lower emissions compared to cattle (Österle, 2008; Bollig, 2016). Follow-up studies on the long-term effects of the pandemic and other shock events on economic coping strategies are required to assess how these events accelerate existing trends and impact GHG emissions from livestock.

Our results highlight the utility of proxy data to identify overarching trends within the three-part framework. While proxy data allowed for qualitative analysis of GHG emissions in this study, it was not possible to quantitatively evaluate GHG emissions in the absence of local to regional estimates of GHG emissions in these systems. Results of this study therefore require ground-truth measurements of biophysical parameters and monitoring of herd size, feed availability and quality, and movement. Studies conducted elsewhere in East Africa have estimated regional to local emission factors for livestock production systems associated with specific agro-ecological zones (Goopy et al., 2018; Ndung'u et al., 2018), but no studies on emission factors for extensive livestock production systems in ASALs have been conducted to this point. There is still considerable uncertainty and a wide range of estimates with respect to the total herd size in East Africa, and for extensive livestock systems in ASALs in particular (Robinson et al., 2007; Wint and Robinson, 2007). Future research should focus on the critical need to develop emission factors for livestock in extensive livestock systems and accurate measures of herd size at broad geographic scales to accurately quantify GHG emissions from livestock in SSA. Such measures would also allow for quantification of GHG emission intensities, which measure the quantity of GHG emitted per unit of animal product (i.e., milk, meat) and thus provide an indicator of production efficiency (Brandt et al., 2018; Ericksen and Crane, 2018; Ali et al., 2019; Goopy, 2019; Brandt et al., 2020; Goopy et al., 2020).

Future work could benefit from using the three-part framework developed here as a tool for evaluating the effects of shocks, such as major droughts (e.g. as predicted for the long rainy season in East Africa in 2021 due to La Niña conditions), as well as the effects of COVID-19 for other locations. Further research using the framework developed here could be paired with more long-term monitoring of biophysical aspects of livestock systems in Northern Kenya and SSA in general to provide a more accurate picture of baseline GHG emissions from these systems, and serve as predictor of the magnitude and direction of changes associated with specific shock events. Therefore, we recommend more intensive collection of spatially explicit and continuous data to monitor the effects of shock events, such as droughts and the COVID-19 pandemic, on GHG emissions from livestock in Africa using the three-part framework developed here.

Declaration of Competing Interest

We declare no conflict of interest for any of the authors associated with publication of this manuscript.

Acknowledgements

This study was funded by the German Federal Ministry for Economic Cooperation and Development (BMZ issued through GIZ) through the "Programme of Climate Smart Livestock" (PCSL, Programme No. 2017.0119.2). The authors further acknowledge the CGIAR Fund Council, Australia (ACIAR), Irish Aid, European Union, IFAD, the Netherlands, New Zealand, UK, USAID and Thailand for funding the CGIAR Research Program on Livestock. For data collection, we are grateful to the ILRI Livestock-CRP and support from USAID Agreement Number AID-OAA-L-12-00001 that was awarded to The Regents of the University of California for the Markets, Risk and Resilience Innovation Lab. The content of this article does not necessarily reflect the position of anyone other than the authors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2021.103203.

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DOI: https://doi.org/10.1016/j.agsy.2021.103269

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Agricultural Systems xxx (xxxx) xxx

Contents lists available at ScienceDirect

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Corrigendum

Corrigendum to "A framework for assessing the effects of shock events on livestock and environment in sub-Saharan Africa: The COVID-19 pandemic in Northern Kenya" [Agricultural Systems Vol. 192 (2021) 103203]

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The authors regret that the following text should be added : "We gratefully acknowledge funding support from the Agricultural Technology Adoption Initiative (ATAI), grant number S5081."

The authors would like to apologise for any inconvenience caused.

DOI of original article: https://doi.org/10.1016/j.agsy.2021.103203.

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https://doi.org/10.1016/j.agsy.2021.103269