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Managing climate risk in livestock production in South Africa: How might improved tailored forecasting contribute?

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ABSTRACT

The 2015–2017 summer rainfall seasons in both South and southern Africa saw drought and heat stress severely impacting the livestock production sector, as well as agriculture more broadly. Although the region has a longstanding operational forecasting system; tailored forecasting, including that designed for the livestock sector, has declined in presence and operational use in recent years. The potential use of such information to enable the livestock sector to better cope with difficult seasons such as those of 2015–17 is clear. A range of promising initiatives attempt to move South Africa (and the broader southern Africa region) in the direction of improved tailored forecasting, integrated, in part, into the operational system. A number of gaps in application remain, however, and the paper concludes with a discussion as to how the field might move forward, particularly in the light of possible increased frequency of drought and heat stress in the future.

1. Introduction

While forecasting and early warning for agriculture in South Africa has tended to traditionally focus more on the cropping sector, the importance of livestock production has been increasingly recognized in recent years. Changes have been evident in both the emerging and commercial sectors, including changes in consumption patterns (increased demand for meat and dairy; changes in demand for certain types of meat); as well as the increasing importance of the wildlife and ranching sector (see, for example, Archer et al., 2017; Thornton & Herrero 2015; Boone et al., 2018; Godde et al., 2018; Herrero et al., 2015).

From 2015 to 17, summer rainfall season drought in the southern African region severely impacted the entire agricultural sector, with substantive negative impacts on livestock, including condition loss and mortality (Archer et al., 2017). The Southern African Development Community (SADC) mid-December Agrometeorological Update (SADC 2015) showed below normal rainfall throughout much of terrestrial SADC; and delayed rainfall onset in parts of South Africa and Lesotho. In addition, extremely high temperatures were experienced over the southern half of the region, including key livestock production areas. Tailored forecasting to support the livestock production sector in South Africa and in the region remains, however, an area of limited focus, and much of the discussion during the 2015/6/7 seasons at both national and regional levels tended to focus rather more on the cropping sector (for example, discussions undertaken at the SADC Disaster Risk Reduction mid-season meetings).

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2. Climatic risks to livestock in South Africa

The livestock production sector in South Africa is vulnerable to climatic risk, and previous (and ongoing) case studies further show how implications may be severe. In the Suid Bokkeveld (arid western South Africa), for example, where for the majority of farmers, livestock comprises a main source of income, in a participatory research study, researchers working with farmers focused on climatic risk impacts on small stock. With analysis including weekly condition assessments and behavioural observation (as well as weather data measurement), significant lamb mortality due to cold conditions was observed, as well as loss of condition during the dry season (as expected – it should be noted that the dry season is, largely, in summer in this region, bar a small amount of cross-over summer rainfall) (Januarie et al., 2015). In Namaqualand, also in western arid South Africa, researchers find that loss of condition during the dry season makes livestock vulnerable to cold conditions and extreme temperatures, contributing to lambing mortality and loss (Bourne pers comm). In both the Suid Bokkeveld and Namaqualand, lamb mortality was high during cold spells, representing significant loss to farmers in these communal areas, particularly when coupled with poor forage conditions due to drought (a so-called 'combination event').

In the Limpopo region, Stroebel et al. (2011) found that the impacts of drought were very evident in cattle herds in their study (including critical impacts on herd health and size). Researchers focused specifically on decisions on whether or not to cull or sell, finding that such decisions tend to be complex, and linked to the many faceted ways in which cattle are viewed and valued – understanding that is required if recommendations around managing cattle herd sizes to respond to climatic risk are to be undertaken. Considering longer term climate projections, Archer van Garderen (2011) found that heat stress thresholds considered to be of concern to all types of livestock are more likely to be exceeded in the future, in particular areas in the subcontinent, with implications for condition, morbidity and mortality. Updated climate change projections for southern Africa show this as a continuing robust finding. In the case of chickens in northern South Africa, Nyoni et al. (2019) found that even genetically diverse, fairly hardy so-called 'village chickens' were prone to loss of condition and productivity in hot summer seasons.

Finally, in a survey of commercial livestock farmers and land managers in the Eastern Karoo, South Africa, in mid-2020/early 2021, farmers indicated that the impacts of the recent multi year drought were extremely severe (although not unprecedented). Impacts included loss of livestock condition, and negative implications for reproduction (including diminished conception rates), diminished milk production; and severe loss of income (as a result of a combination of factors, including the need to purchase animal feed, loss of income due to destocking; and poor commodity prices due to the drought). We discuss use of any predictive climate and weather information (including potential use) by such farmers later in the article.

3. Aspects of seasonal forecast development in southern Africa

Seasonal forecasting in South Africa has a history characterized by both gradual and sudden improvements in capability and forecast performance, with continued increases in complexity. South Africa, represented by the South African Weather Service (SAWS), is recognised by the World Meteorological Organization as a Global Producing Centre for Long-Range forecasting. In addition, a number of local institutions have developed sustained seasonal forecast modelling expertise in their own right (Klutse et al., 2016; Landman, 2014; Landman & Beraki, 2012; Landman et al., 2005; Beraki et al., 2015; Landman & Beraki, 2012; Landman et al., 2012, Landman et al., 2014). For example, a seasonal forecasting initiative is active at the University of Pretoria, with a key focus, in addition to the use of regional climate models (Ratnam et al., 2016), on the use of the North American Multi-Model Ensemble NMME; (Kirtman et al., 2014) to support the development of rainfall and temperature forecast products for SADC, as well as the development of tailored products (see Figs. 1 and 2).

In some cases, archived and real-time global climate model forecasts are being used to produce tailored forecasts for a range of

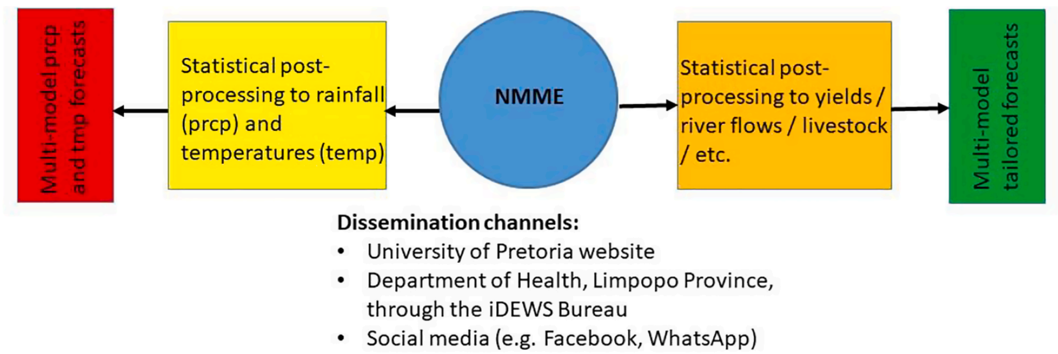

Fig. 1. Representation of the South African forecasting system for rainfall and temperatures (left side of figure) and tailored products (right side of figure). The institution and models named in the circles are those currently contributing to the official seasonal forecasts of the South African Weather Service. We suggest that the UP modelling effort will, for the immediate future, mainly contribute towards tailored products. Dissemination channels are shown, including social media dissemination. (MOS: Model output statistics; SAWS: South African Weather Service; CSIR: Council for Scientific and Industrial Research; UP: University of Pretoria).

sectors, including incidence of seasonal malaria in the Limpopo province, South Africa (Landman et al., 2020), inflows into Lake Kariba (Muchuru et al., 2016), and for estimation of end-of-season crop yields (Landman et al., 2019b). Fig. 1 is a schematic of how a dataset of climate model forecasts supports a multi-model approach for rainfall and temperature forecasts in real time (left side of figure), and how the same forecasting approach can be used to develop tailored predictions (right side of figure). These forecasting systems consist of a number of tiers: firstly, each model's output is statistically recalibrated or downscaled and, subsequently, combined into a multi-model system (Landman et al., 2012). For rainfall and temperature, the statistical post-processing or downscaling is applied to gridded data such as the Climatic Research Unit (CRU) data (Mitchell & Jones 2005). For tailored products, statistical downscaling can typically be undertaken for those examples mentioned above - including malaria, crop yields, river flows and, significantly, livestock production relevant metrics (e.g. Malherbe et al., 2014). We discuss tailored forecasting in more detail below.

The evolution of South Africa's seasonal forecasting systems from statistical to fully coupled models is correlated with a subsequent improvement in forecast skill (Landman 2014), although seasonal rainfall variations are best predicted only when the eastern equatorial Pacific Ocean is either in a warm or a cold phase (Landman & Beraki 2012). During ENSO-neutral years (i.e., neither a warm nor cold phase), seasonal forecasts for southern Africa are found to be much less useful – a fact of particular interest, given our finding presented later in the article that some livestock farmers only consider forecasts when El Niño is mentioned (not La Niña, interestingly – which might be a particular feature of this area). Notwithstanding this limitation, there is skill in predicting seasonal extremes such as severe droughts and excessively wet seasons (Landman & Beraki, 2012; Landman et al., 2005, 2014). Tailored forecasting has been tested for agricultural and hydrological sectors in southern Africa by using the output from these models (for example, Malherbe et al., 2014; Muchuru et al., 2015). In our concluding discussion, we focus specifically on common predictive products used by farmers in south and southern Africa, including verification statistics.

4. Tailored forecasting for the agricultural sector – What is currently available?

To increase the potential usefulness of forecast information, local relevance to what really matters to farmers must be addressed in such a way as to support understanding of how their farming systems and households might be impacted by elements such as lack of rainfall, soil moisture, extreme temperatures or river flow, for example (e.g. Andersson et al., 2019).

For example, an extremely wet season occurred over the larger part of southern Africa during the 2010/11 La Niña season. The wet conditions caused significant societal impacts over parts of southern Africa, including impacts caused by flooding events in the

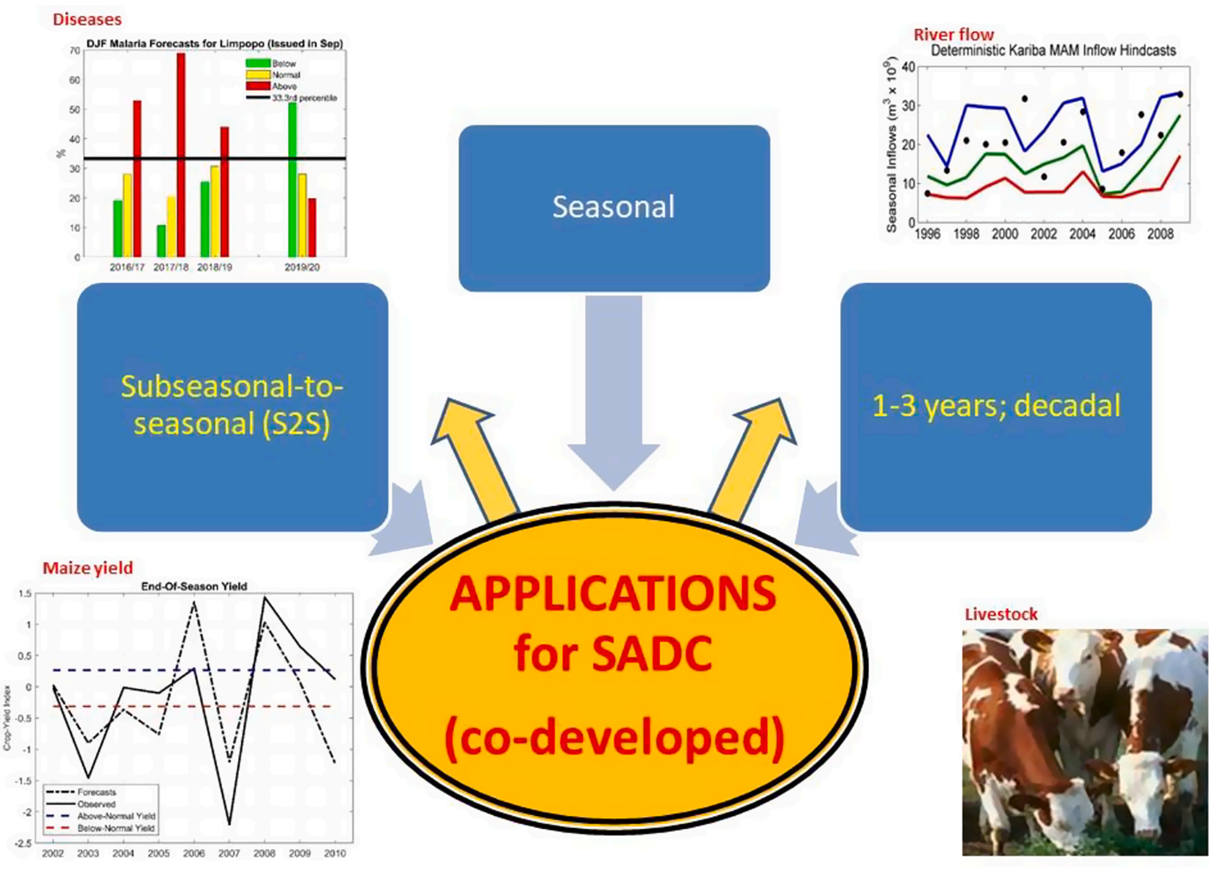

Fig. 2. Integrated tailored forecasting for the SADC region: sub-seasonal to decadal modelling and applications.

Zambezi River catchment – as well as severe impacts on livestock and crops (including loss of planted areas, forage loss and loss of livestock). Seasonal rainfall predictability over the catchment area was subsequently, as mentioned earlier, tested (Muchuru et al., 2014), and a model to predict inflow into the lake was also developed (Muchuru et al., 2016). Testing of this model included calculating its reliability and discrimination attributes over an independent test period. The model, in general, performed best during the austral mid-summer, when the onset of inflows into the lake occur, and during the main inflow season in autumn. Seasonal rainfall in the catchment, as well as inflow into the lake, were then found to be predictable with several months lead-time and, thus, the impacts caused by the 2010/11 flooding could, to a large extent, have been averted had the extremely wet season been predicted in real-time and had decision makers and/or risk managers been able to access, understand and heeded potential warnings of an imminent extremely wet season. In fact, it was demonstrated (Muchuru et al., 2016) that a forecast of high probabilities of high inflow levels for the 2010/11 season could have been successfully made with lead-times up to 5 months.

Another example of a so-called tailored forecast system with demonstrable capabilities is a crop yield prediction model for dry-land end-of-season maize yields and accumulated river flows over north-east South Africa (Malherbe et al., 2014). This study demonstrated the potential for a commodity-orientated operational forecast system for application in agriculture, since the model should be able to assist both dry-land crops and irrigation farmers in the area alike (with, again, available support, and were the outputs accessible and understandable – see our concluding discussion). The forecast would be aimed at influencing early-season decision making with regards to planting density, crop type and cultivar as well as potential for irrigation through the growing season. Rivington and Koo (2010) undertook a survey on crop model development and application, receiving a total of 457 responses. Of the total number of responses, a quarter was from Africa, and respondents were mostly developers and/or users of crop models, with a large majority of 122 separate models covered being crop specific. For the question of "How can improvement of the input weather data be best achieved to increase the quality of crop model outputs?", the availability of weather data at a finer spatial scale of coverage was seen to be the most important. Better interpolation techniques (between meteorological stations) and improved techniques for estimating missing data were also seen as important.

Looking more specifically at tailored forecasting with utility for the livestock section, according to Rivington and Koo (2010), the development of grass modelling capabilities in relation to their most important processes shared common areas with general crop models (water use, light interception, nitrogen etc.), but had additional requirements. These requirements centred on the response of the plants to grazing and cutting, and the processes of translocation (biomass partitioning) of resources within the plant between below and above ground and interaction with grazing. Only 39% of the responses in the grass modelling section of the survey indicated that their models represent grass, or have linkages to livestock production. Of these positive responses indicating greater potential for use in an operational grazing advisory capacity, 20% said their model was grass specific, 57% said their model was part of a wider range of crop representation, and only 23% indicated that it was part of a decision support system. Snow et al. (2014) listed some of the notable models that are able to simulate pastoral farming systems, including APSIM (Holzworth et al., 2014), Dairy Mod and the SGS Pasture Model (Johnson et al., 2008), the well-known GRAZPLAN (Donnelly et al., 2002), as well as the Integrated Farm System Mode (Rotz et al., 2012).

The PUTU 11 model was developed specifically for the southern African context and simulates rangeland (or 'veld', as the term is used in the region) conditions using weather, soil and plant physiological data (Fouche, 1984). The model simulates the growth, development and dry matter production of *Themeda Triandra* grass, a common, palatable species in the grasslands and savannas of Africa. Current veld conditions are calculated and expressed as a percentage deviation from the long term situation. However, although the model was used for some years as part of the regional operational veld forecasting system, 'VeldInfo'; and was then subsequently run by the short term insurance company SANTAM (working within southern Africa and internationally), as part of its in-house operations, it has not been run in an operational sense for some years (SANTAM pers comm, 2015).

The National Agrometeorological Committee in South Africa issues general information to extension officers through representatives of the provincial departments of Agriculture. Relevant observed weather and vegetation conditions together with the expected situation based on the SAWS 3-monthly probabilistic seasonal forecast are considered. Management strategies for livestock are suggested based on the information and typical background climate, but (effectively) reintroducing more technically targeted tailored forecasting, with strongly evidence based strategies, into the operational system is of critical importance.

5. Emerging initiatives for tailored forecasting for livestock and potential applications

Several emerging (and, in some cases, reinvigorated) initiatives in tailored forecasting specifically for the livestock production sector are starting to show promise. Firstly, biomass production, including grazing, has a strong positive relation to total seasonal rainfall over semi-arid subtropical regions (e.g. Deshmukh 1984). Relatively high predictability of seasonal rainfall over some of these areas, such as the Limpopo River Basin (Landman et al., 2012), creates an opportunity to create tailored products based on observed vegetation activity and seasonal rainfall forecasts. Such outlooks can inform decision makers, including livestock farmers, regarding expected possible deviations from the carrying capacity, and may inform strategies before and during growing seasons (Maluleke et al., 2019). Effectively, grazing practices can be regulated (or better informed) with the aid of seasonal forecasts and remote sensing information in order to ensure that farms and rangelands remain productive for many years to come (Han et al., 2008). Tailored seasonal forecasts can assist farmers and managers in making informed decisions when it comes to scheduling grazing periods, burning of veld, vaccination, emigration decisions and buying of livestock feed and protein supplements – as well as decisions around stocking and destocking (and, importantly, their timing); which are, of course, critical decisions in most livestock production systems. The packaging of this information is, however, crucial as it must be customized to meet user needs (Ziervogel et al., 2006; Moeletsi et al., 2013; Archer et al., 2019).

Estimating grass biomass constitutes a vital management strategy that can be achieved through a range of methods, including cutting and weighing of samples and the disc pasture meter method. Observations and measurements of above ground biomass provide farmers and managers with a good indication of available forage for the upcoming season, as well as soil erosion potential (Thursby et al., 2002; Schino et al., 2003). Knowledge of available pasture can assist farmers to safeguard against overgrazing and stay within carrying capacity parameters (particularly during a poor season).

Secondly, clear applications are evident in terms of heat stress – in terms of vulnerability to heat stress of livestock, and the use of forecasts specific to heat stress risk. For example, dairy cattle, with their high metabolism, are well-known for their sensitivity to heat stress, which causes decreased milk production. Should ambient temperature exceed the upper limit of their comfort zone, cows utilize more energy for cooling down, and less for milk production. The skill of climate models to predict seasonal maximum temperature extremes has been demonstrated for southern Africa (Lazenby et al., 2014) – the models can predict skillfully when there is a high likelihood of southern Africa experiencing extremely high seasonal maximum temperatures during mid to late summer. However, the heat stress challenge is exacerbated in humid conditions, when higher concentrations of atmospheric moisture renders evaporative heat loss more difficult in livestock. Medium-range and seasonal prediction models for heat stress in cattle are being developed as an early warning system for farmers based on the temperature-humidity index (THI), an internationally used parameter indicative of heat stress in animals. By alerting farmers in advance of areas where cattle could be at risk, appropriate short term precautions could be implemented to mitigate the effect of the heat stress during the hot summer months – for example through provision of supplemental water, temporary shade; and/or rotation to cooler pastures with more natural shade (where available); or introduction of night grazing (as is the case in some areas of northern and central Namibia).

Lastly, medium-range and seasonal prediction models may also be used to develop early warning systems for viral diseases such as Rift Valley fever (RVF), a zoonotic mosquito-transmitted disease causing human mortality and economic impacts due to loss of livestock, and which is usually associated with a La Niña event (for South Africa – see, for example, NASA 2020). Analysis of climate data for the 2008–2011 RVF outbreaks in South Africa revealed a pattern of incessant and widespread seasonal rainfall, resulting in significant soil saturation, which persisted for some time before an explicit rainfall event created ideal eco-climatic conditions for the emergence of large populations of mosquito vectors and subsequent outbreaks of the disease (Pienaar, 2011; Williams et al., 2016).

6. What is missing, and how to move forward?

Despite the importance of the agricultural and, more specifically, the livestock sector in South Africa, and the aforementioned comparatively robust operational status of seasonal forecasting, tailored forecasting for livestock production in the region remains sparse, and only partly integrated into the operational early warning system. We have outlined some promising initiatives here, both for agriculture more broadly and for livestock - but what is currently underway is funded and supported in a fairly fragmented manner –with significant variations amongst countries. In addition, current and emerging initiatives have a very technical focus – there is limited user outreach, and needs analysis, and testing and refinement is largely undertaken on a project basis and timescale.

To consider possible use of the system shown in Fig. 1 (where channels of dissemination are shown), we worked from the ground up with the aforementioned sample of livestock farmers/land managers in the Eastern Karoo region of South Africa, considering both actual and potential use on the ground.

It should be noted, first, that commenting on the accuracy of these products for South Africa is a much more challenging task, as verification studies for these products over the region of interest are very seldom conducted (a clear gap). In terms of the verification of the public weather forecast system in South Africa, the South Africa Weather Service (SAWS) Annual Report 2019/2020 comments on the accuracy of their severe weather warnings. An "accurate" forecast - or warning - is one with a small amount of error (with the actual amount depending on the application). It was reported that severe weather warnings (for example high fire-danger, severe thunderstorms, etc.) were predominantly accurate. Considering aerodrome warnings issued by SAWS during the year under review, the accuracy of warnings were also high. When stakeholders were questioned regarding the quality of the aviation forecast products offered by SAWS, only a small percentage of stakeholders rated the quality of these products as poor, while a total of 97% believed the offered products are of good or excellent quality (SAWS, 2020). It is interesting to note is that, while SAWS and their stakeholders consider the products offered by to be accurate and of good quality, ratings and installs of the app that they produce (see Fig. 1) are relatively low.

In our survey of the aforementioned group of livestock famers/land managers in the Eastern Karoo, we attempted to further consider what the actual use of such predictive products (including available tailored forecasting) is on the ground. Of course, any one group cannot be perfectly representative of all livestock farmers in South Africa, but our reasoning was that a (relatively) well-resourced and technologically connected farming group is a useful test case – since if they have little use or access, less well-resourced farmers are even less likely to access and/or use these products. Our findings, despite the involvement of several authors in forecast applications for some time, surprised us.

Very few farmers make use of weather forecasts (and none make use of tailored predictive products for the livestock sector). Of those indicating accessing weather forecasts, only two (out of twelve respondents) indicated that they make use of the SAWS forecasts, and in only two cases, when the El Niño phenomenon is mentioned as a possibility. In follow up focused discussions (with individuals – since group formats were not possible) with those who indicated that they make use of weather forecasts, in fact, in this group of farmers, none really make robust use of the forecasts. It would be best to describe the access to forecasts as simply a reference or a 'touch point'; without changing actual operations in any concrete way. This is, of course, not unusual – it is a fairly longstanding finding in forecast applications studies. Finally, in follow up focus discussions with the few farmers who refer to forecasts, we asked them to characterize how they might use a tailored predictive product for the livestock section. All were, in fact, positive; indicating that if they had trust in such a product (for example, access to verification information); they would make clear use of it in grazing and land management operations (including provision of supplemental water, and changed rotational grazing, including access to higher carrying capacity rangeland – where available).

Further gaps in terms of tailored forecasting for livestock remain, of course. Such gaps include a rather limited focus, thus far, on either cold stress impact, or so-called combination events (as mentioned earlier in the Namaqualand case study). In Fig. 2, below, we show some examples of how tailored forecasting might work in practice, with livestock early warning (with a range of measures) as one element of a full suite of offerings referring specifically to the key areas for application model development - namely health (disease), hydrology (river flows) and agriculture (crop yields, and the focus of this paper, livestock), currently being addressed in South and southern Africa. The time ranges depicted in the figure go beyond short-range weather forecasting to include the extended-range, long-range (seasonal time scale), and multi-year predictions. Users are, of course, also interested in spatial scale – and some tailored forecasts (for example, tailored forecasts for heat stress in areas with good observational data) may be useful on a scale relevant to large farming blocks (as one example). Our work for this article shows, of course, that such supply end work on tailored forecasting is largely irrelevant without strategically targeted work with users to understand user needs, and address this in system design (including, for example, the finding above regarding farmer requests for information on verification and skill).

Clearly, tailored forecasting to serve the livestock sector in South Africa, as well as the broader region, needs substantive attention, but beyond simply increased resources, initiatives must be better coordinated and engaged with in a programmatic way, with strategic approaches to user outreach and needs analysis – including, as indicated above, clear access to verification statistics and information regarding tailored forecast skill. Such an emphasis applies, of course, beyond the livestock sector, to tailored forecasting for multiple sectors (selected examples of which are shown in Fig. 2) – and there are clear opportunities for both strong ongoing engagements with the Southern African Regional Climate Outlook Forum (SARCOF) process, as well as national level focus and engagement with country National Meteorological Services. The experiences of, for example, the Greater Horn of Africa Climate Outlook Forum (GHACOF) and the IGAD Climate Predication and Applications Centre (ICPAC) and their involvement in tailoring sector specific forecasts (including those for livestock) is highly valuable in this regard.

The best approach here would be to engage in co-production between tailored forecast designers (using multiple institutions, including those who have experience in acting as a 'boundary organization'), and potential users, as has been proposed for the water sector (Morss et al., 2005), with iterative redesign of systems according to (evolving) clearly indicated user needs. Elements of this work are underway, including ongoing initiatives undertaken directly with livestock farmers and land managers in semi-arid rangeland. South Africa, and the broader region, may learn from other areas with similar uptake and utility challenges (Landman et al., 2019) – a priority, since, as mentioned earlier, it is likely that elements of the current climatic impacts on livestock will increase in frequency. We may well see more seasons similar to the 2015/6/7 season, with its aforementioned severe impacts on the agricultural sector. Evolved approaches here should form part of a swiftly developed improved response.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Andersson, L., Wilk, J., Graham, L.P., Wikner, J., Mokwatlo, S., Petja, B., 2019. Local early warning systems for drought– Could they add value to nationally disseminated seasonal climate forecasts? Weather Clim. Extrem. 100241.

Archer, E.R.M., Landman, W.A., Tadross, M.A., Malherbe, J., Weepener, H., Maluleke, P., Marumbwa, F.M., 2017. Understanding the evolution of the 2014–2016 summer rainfall seasons in southern Africa: Key lessons. Clim. Risk Manage. 16, 22–28.

Archer, E., Landman, W., Malherbe, J., Tadross, M., Pretorius, S., 2019. South Africa's winter rainfall region drought: A region in transition? Clim. Risk Manage. 25, 100188.

Archer van Garderen, E., 2011. (Re) considering cattle farming in Southern Africa under a changing climate. Weather Clim. Soc. 3 (4), 249–253.

Boone, R.B., Conant, R.T., Sircely, J., Thornton, P.K., Herrero, M., 2018. Climate change impacts on selected global rangeland ecosystem services. Global Change Biol. 24 (3), 1382–1393.

Deshmukh, I., 1984. A common relationship between precipitation and grassland peak biomass for east and southern Africa. Afr. J. Ecol. 22 (3), 181–186.

Donnelly, J., Freer, M., Salmon, L., Moore, A., Simpson, R., Dove, H., Bolger, T., 2002. Evolution of the GRAZPLAN decision support tools and adoption by the grazing industry in temperate Australia. Agric. Syst. 74 (1), 115–139.

Fouche, H. J., 1984: Ondersoek na die gebruik van die PUTU II simulasiemodel en Palmerindeks vir die karakterisering van droogtetoestande.

Godde, C.M., Garnett, T., Thornton, P.K., Ash, A.J., Herrero, M., 2018. Grazing systems expansion and intensification: drivers, dynamics, and trade-offs. Global Food Secur. 16, 93–105.
Han, J.G., Zhang, Y.J., Wang, C.J., Bai, W.M., Wang, Y.R., Han, G.D., Li, L.H., 2008. Rangeland degradation and restoration management in China. Rangeland J. 30 (2), 233–239.
Herrero, M., Wirsenius, S., Henderson, B., Rigolot, C., Thornton, P., Havlík, P., De Boer, I., Gerber, P.J., 2015. Livestock and the environment: what have we learned in the past decade? Annu. Rev. Environ. Resour. 40, 177–202.
Holzworth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., 2014. APSIM–evolution towards a new generation of agricultural systems simulation. Environ. Modell. Software 62, 327–350.
Januarie, D. B., Archer van Garderen, E.R.M. , Hetem, R.S. and Koelle, B., 2015: Heat stress and livestock farming in the Suid Bokkeveld: some emerging results. Presentation at the Arid Zone Ecology Forum, October 2015, South Africa.
Johnson, I., Chapman, D., Snow, V., Eckard, R., Parsons, A., Lambert, M., Cullen, B., 2008. DairyMod and EcoMod: biophysical pasture-simulation models for Australia and New Zealand. Aust. J. Exp. Agric. 48 (5), 621–631.
Kirtman, B.P., Min, D., Infanti, J.M., Kinter, J.L., Paolino, D.A., Zhang, Q., Van Den Dool, H., Saha, S., Mendez, M.P., Becker, E., Peng, P., 2014. The North American multimodel ensemble: phase-1 seasonal-to-interannual prediction; phase-2 toward developing intraseasonal prediction. Bull. Am. Meteorol. Soc. 95 (4), 585–601.
Klutse, N.A.B., Abiodun, B.J., Hewitson, B.C., Gutowski, W.J., Tadross, M.A., 2016. Evaluation of two GCMs in simulating rainfall inter-annual variability over Southern Africa. Theor. Appl. Climatol. 123 (3–4), 415–436.
Landman, W.A., Archer, E. and Tadross, M., 2019: How costly are poor seasonal forecasts? Peer reviewed abstracts, 35th Annual conference of the South African Society for Atmospheric Science, Vanderbijlpark, 8 to 9 October 2019, pp 60-63. ISBN 978-0-6398442-0-6.
Landman, W.A., Sweijd, N., Masedi, N., Minakawa, N., 2020. The development and prudent application of climate-based forecasts of seasonal malaria in the Limpopo Province in South Africa. Environ. Dev. 35, 100522.
Landman, W.A., Barnston, A.G., Vogel, C., Savy, J., 2019b. Use of ENSO-related seasonal precipitation predictability in developing regions for potential societal benefit. Int. J. Climatol. 39, 5327–5337. https://doi.org/10.1002/JOC.6157.
Landman, W.A., 2014. How the International Research Institute for Climate and Society has contributed towards seasonal climate forecast modelling and operations in South Africa. Earth Perspectives 1 (1), 22.
Landman, W.A., Beraki, A., 2012. Multi-model forecast skill for mid-summer rainfall over southern Africa. Int. J. Climatol. 32 (2), 303–314.
Landman, W.A., Botes, S., Goddard, L., Shongwe, M., 2005. Assessing the predictability of extreme rainfall seasons over southern Africa. Geophys. Res. Lett. 32, 23.
Landman, W.A., Beraki, A., DeWitt, D., Lötter, D., 2014. SST prediction methodologies and verification considerations for dynamical mid-summer rainfall forecasts for South Africa. Water SA 40 (4), 615–622.
Landman, W. A., DeWitt, D., Lee, D-E., Beraki, A., and Lötter, D., 2012: Seasonal rainfall prediction skill over South Africa: one-versus two-tiered forecasting systems. Weather Forecast., 27:2, 489-501.
Lazenby, M.J., Landman, W.A., Garland, R.M., DeWitt, D.G., 2014. Seasonal temperature prediction skill over southern Africa and human health. Meteorol. Appl. 21 (4), 963–974.
Malherbe, J., Landman, W.A., Olivier, C., Sakuma, H., Luo, J.J., 2014. Seasonal forecasts of the SINTEX-F coupled model applied to maize yield and streamflow estimates over north-eastern South Africa. Meteorol. Appl. 21 (3), 733–742.
Maluleke, P., Landman, W.A., Malherbe, J., Archer, E., 2019. Seasonal forecasts for the Limpopo Province in estimating deviations from grazing capacity. Theor. Appl. Climatol. 137 (3–4), 1693–1702.
Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int. J. Climatol. J. Roy. Meteorol. Soc. 25 (6), 693–712.
Moeletsi, M.E., Mellaart, E.A.R., Mpandeli, N.S., Hamandawana, H., 2013. The use of rainfall forecasts as a decision guide for small-scale farming in Limpopo Province, South Africa. J. Agricult. Educat. Extens. 19 (2), 133–145.
Morss, R.E., Wilhelmi, O.V., Downton, M.W., Gruntfest, E., 2005. Flood risk, uncertainty, and scientific information for decision making: lessons from an interdisciplinary project. Bull. Am. Meteorol. Soc. 86 (11), 1593–1602.
Muchuru, S., Landman, W.A., DeWitt, D., Lötter, D., 2014. Seasonal rainfall predictability over the Lake Kariba catchment area. Water SA 40 (3), 461–470.
Muchuru, S., Landman, W.A., DeWitt, D., 2016. Prediction of inflows into Lake Kariba using a combination of physical and empirical models. Int. J. Climatol. 36, 2570–2581. https://doi.org/10.1002/joc.4513.
NASA 2020: ENSO Teleconnections and Rift Valley fever (RVF) Outbreaks [online]. Available from: https://svs.gsfc.nasa.gov/4784 (Accessed 12 February 2021).
Nyoni, N., Grab, S., and Archer, E.R.M., 2019: Heat stress and chickens: climate risk effects on rural poultry farming in low-income countries. Clim. Dev., 11:1, 83-90.
Pienaar, N.J., 2011. A Retrospective Analysis of the Epidemiology of Rift Valley Fever in South Africa. University of Pretoria, MSc.
Ratnam, J.V., Behera, S.K., Doi, T., Ratna, S.B., Landman, W.A., 2016. Improvements to the WRF seasonal hindcasts over South Africa by bias correcting the driving SINTEX-F2v CGCM fields. J. Clim. 29 (8), 2815–2829.
Rivington, M., Koo, J., 2010. Report on the meta-analysis of crop modelling for climate change and food security survey. CGIAR 70, pp.
Rotz, C.A., Corson, M.S., Chianese, D., Montes, F., Hafner, S.D., Coiner, C., 2012. The integrated farm system model. References manual version, 3.
SADC, 2015: Food Security Early Warning System: 04, 1-2.
Schino, G., Borfecchia, F., De Cecco, L., Dibari, C., Iannetta, M., Martini, S., Pedrotti, F., 2003. Satellite estimate of grass biomass in a mountainous range in central Italy. Agrofor. Syst. 59 (2), 157–162.
Snow, V.O., Rotz, C.A., Moore, A.D., Martin-Clouaire, R., Johnson, I.R., Hutchings, N.J., Eckard, R.J., 2014. The challenges–and some solutions–to process-based modelling of grazed agricultural systems. Environ. Modell. Software 62, 420–436.
South African Weather Service (SAWS), 2020: South Africa Weather Service Annual Report 2019/2020. ISBN: 0-621-48140-2.
Stroebel, A., Swanepoel, F., Pell, A., 2011. Sustainable smallholder livestock systems: A case study of Limpopo Province, South Africa. Livestock Sci. 139 (1–2), 186–190.
Thornton, P.K., Herrero, M., 2015. Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. Nat. Clim. Change 5 (9), 830–836.
Thursby, G.B., Chintala, M.M., Stetson, D., Wigand, C., Champlin, D.M., 2002. A rapid, non-destructive method for estimating aboveground biomass of salt marsh grasses. Wetlands 22 (3), 626–630.
Williams, R., Malherbe, J., Weepener, H., Majiwa, P., Swanepoel, R., 2016. Anomalous high rainfall and soil saturation as combined risk indicator of Rift Valley fever outbreaks, South Africa, 2008–2011. Emerg. Infect. Dis. 22 (12), 2054.
Ziervogel, G., Bharwani, S. and Downing, T.E., 2006: November. Adapting to climate variability: pumpkins, people and policy. In Natural Resources Forum (Vol. 30, No. 4, pp. 294-305). Oxford, UK: Blackwell Publishing Ltd.