Drought, climate change and sustainability of water in agriculture: A roadmap towards the NWRS2

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The frequency and intensity of drought, extreme events and high wind velocities in South Africa are expected to increase in the next century as a result of the changing climate. The National Water Resource Strategy 2 (NWRS2) has set out the general and strategic directions for water resources management in the country for the next 20 years. However, the strategy does not draw a framework tailored specifically for agricultural use, with specific measures and goals. Therefore, to reach sustainability of water in agriculture, four major strategic goals are suggested, on which research institutions can focus and promote through good governance. The strategy emphasises: (1) crop research to find new drought- and heat- tolerant and resistant breeds and varieties; (2) intensified research in agricultural practices; (3) increasing the efficiency of water use within agriculture; and (4) integrating all these strategic goals within a sustainable research framework. Finally, the research calls for rapid action and implementation.

Significance:

- The framework is proposed for stakeholders and policymakers in higher education, agriculture and resources management in South Africa for new research horizons at national level to improve overall agricultural sustainability by 2030 as stipulated by the Millennium Development Goals.

Introduction

South Africa has a huge territory with a diverse range of climates, but is dominated by a semi-arid climate. The historical annual rainfall varies from less than 100 mm per annum in the west to over 1500 mm in the east; the average rainfall is 450 mm per annum. The year 2015 was characterised by unprecedentedly dry and hot weather – the driest it has been in over a century[1] – with maximum temperature and minimum rainfall records measured in different parts of the country[2,3]. The frequency and intensity of drought and heat events are expected to increase over the next century as a result of the changing climate.[4] According to Solomon et al.[5], the effects will be mainly observed on annual temperatures (with a possible increase of 3.4 °C and up to 3.7 °C in spring) and on rainfall (with a decrease of 23% in winter and 13% in spring).

The current extreme conditions in South Africa have had the same impacts described in the literature (e.g. Parry et al.[6]) – such as severe depletion of water resources (ground and surface water) and, consequently, deterioration of water quality. The impacts have been hard on the agricultural sector, which is extremely sensitive to heat and uses over 60% of the total water resources of the country.[7] Consequently, the whole socio-economic structure of the agriculture-based economy is affected, not to mention the impacts on the environmental health of national ecosystems, the threat to national food security because of the reduction of the harvests and the increase in poverty levels. The industrial and urban sectors have also been strongly affected by this drought, given the water restrictions that have been imposed throughout the country.

The National Water Resource Strategy 2 (NWRS2) – published in 2012 by the Department of Water Affairs – has set out the general and strategic directions for water resources management in the country for the next 20 years to ensure equitable growth and development. The NWRS2 has addressed the management framework at national level according to the Integrated Water Resources Management approach.[8] Integrated Water Resources Management is a cross-sectoral and participatory approach for sustainable development, allocation and monitoring of water resources[9], which, according to the Global Water Partnership[10] is central to achieving the Millennium Development Goals. Further, Integrated Water Resources Management will be instrumental for the 2030 Agenda to target the Sustainable Development Goals on water and water-related targets under other goals.[11,12]

Further, the NWRS2 focused on the importance of reliable information for the implementation success and the partnership between research institutions, industries and local communities. However, these strategic guidelines did not draw any roadmap to reach these promising objectives and achieve the sustainability of the local water resources in agriculture. From another side, the scientific community has called to intensify research on drought mitigation and to find ways involving integrated strategies and measures[13] for farming systems to cope with its effects, especially in the arid and semi-arid areas of southern Africa[14].

In agriculture, there are no versatile solutions for sustainable management of natural resources under drought conditions, but the integration of different measures within one strategy would be an effective one. Herein a framework is presented on the role of universities in collaboration with other national research institutions to gather and analyse reliable data and to promote innovation towards the NWRS2 goals through good governance. The suggested strategy is divided into four main dimensions, covering all aspects of agriculture which play a crucial part in the overall sustainability of water in agriculture: crop research, agricultural practices, irrigation management and sustainability research.

Crop research

Combining plant physiology and genetics is a powerful scientific tool that can be used to increase efficiency and productivity in agriculture. Crop research should focus on plant physiology and plant genomics, as well as breeding for drought- and heat- resistant and tolerant traits.

Agriculture in South Africa is a major source of income and a significant portion of the population depends on agricultural activity. Drought and heat conditions are the main constraints in agricultural areas. According to recent research,[15,16] the problem is very likely to become worse if trends in climate change play out as expected. The foremost challenge is to select cost-effective crops and varieties with drought- and heat-tolerant and resistant traits for different South African agro-climate zones.

While water is crucial for plant growth, some crops can cope with drought conditions (drought-tolerant crops), others have the ability to tolerate substantial dehydration of their tissues and organs as well as overheating conditions (drought-resistant crops), while others are resilient to high temperatures (heat-resistant crops). Although the effect of heat stress is influenced by additional stresses such as drought, it is important to acknowledge the individual consequences of each.[17]

There are numerous crops (staples, field crops, legumes, vegetables and trees) that are naturally drought- and heat- tolerant and resistant; however, integrated research in advanced plant physiology, molecular genomics and biology, and breeding can, under similar conditions, create traits that allow crops to grow successfully in drought-prone environments.[18] The integration of new tools and technologies has great potential for improving outcomes in the future[19] when creating new performant traits or finding desirable traits in wild crop relatives adapted to specific conditions. Even though many scientists believe that genetic engineering is not yet an effective tool to provide drought- and heat-tolerant and resistant crops[20,21], this area of research has substantial future potential. In the meantime, crop breeding (especially the conventional breeding using marker-assisted selection) is an extremely useful technique for breeding complex traits (such as drought tolerance) into improved varieties.[22]

There is a dearth of studies reported in the literature to enable quantification of water consumption and savings as a result of such improved varieties. However, a study has shown that drought-tolerant and drought-resistant traits could improve the yield of maize in Africa by up to 30% under drought conditions when compared with commercial seeds.[23] Furthermore, Gur and Zamir[24] successfully obtained 50% higher yields of tomato, even under drought conditions, by breeding cultivated tomatoes with wild relatives. Deryng et al.[25] found – on a global scale – that by the 2080s, extreme heat stress at anthesis could: (1) double losses of maize yield, (2) reduce projected gains in spring wheat yield by half, and (3) reduce projected gains in soybean yield by a quarter.

Agricultural practices

Biodiversity and healthy soil are central to ecological approaches for more drought-resistant and drought-tolerant farming practices, which is more resilient to extreme events.[26] Practices encouraging biodiversity and soil health would increase the available water for crops and improve sustainability of agricultural production.[27]

Many of these agricultural practices are available and are used in different places in the world to manage crops and soils. They aid in building healthy and resilient soils to cope with drought.[28] In the windy, semi-arid climate of South Africa, in which soils are prone to degradation by salinity and erosion, these practices could: (1) improve soil moisture holding capacity, (2) reduce soil erosion and salinity, and (3) increase biodiversity of the system. For instance, polyculture and the use of cover crops and crop residues are efficient practices used to protect soils from erosion. Methods such as conservation tillage, legume intercrops, manure and composts would help build soils rich in organic matter, enhancing soil structure and mulching. These practices enhance water infiltration and retention, and make nutrients more accessible to the plant.[29,30]

Some of these practices have been studied in Pennsylvania (USA)[31] and the results show that, under severe drought conditions, 'organic animal-based' and 'legume-based cropping' produced 28–34% higher yields for corn and 36–50% higher yields for soybean compared with those after conventional cropping.[32] In Colorado (USA), Peterson and Westfall[27] estimated that the soil 'water storage efficiency' varied between 19% for maximum tillage and 40% for minimum tillage. Consequently, the precipitation use efficiency was estimated to be 1.22 kg/ha/mm for maximum tilled winter wheat compared with 3.25 kg/ha/mm for minimum tillage – i.e. a higher yield under minimum tillage.[27]

Irrigation management

Efficient management of irrigation water requires a systematic approach that considers the optimisation of rainfall use, the treatment and reuse of non-conventional sources of water, the efficiency of irrigation systems and the reduction of on-farm irrigation losses. According to the Department of Water Affairs[7], South Africa has almost reached its limit in developing surface-water sources, and, for various reasons, not many more dams can be built to increase the supply. What can be done, however, is to keep the systems (storage and conveyance) adequately maintained so that the conveyance efficiency is increased to maximum levels. Water lost during transport through canals could cause the conveyance efficiency to decrease to 95%.[32] In South Africa, it was estimated that this efficiency for different irrigation schemes varies between 63% and 86%.[33]

Nevertheless, to increase on-farm water availability, reservoirs for rainwater harvesting (where possible) could be an economic opportunity for farmers in remote areas. Reservoir systems could also provide farmers – especially smallholder farmers[36] – with additional water during drought periods[34,35]. Water treatment and water reuse in agriculture – despite the quality concerns that it may raise[37] – could be another source of water for irrigation if managed properly and monitored periodically[38].

Furthermore, not all water taken from a source reaches the field, and the plants do not use all the water arriving at the field. Besides the conveyance efficiency, there is a 'field application efficiency' (EA) which reflects the volume of water effectively used by the plants. The EA depends on the irrigation system used and the level of on-farm management[32]. In theory, EA could vary from 60% for surface irrigation, 70% for sprinkler systems and 90% for drip systems[32], but in South Africa, Reinders[39] estimated that the EA varies between 76% and 82% for different sprinkler and drip systems on different sugarcane fields. Finally, according to Wallace[40], about 44% of the total water resource at source is lost between storage and conveyance, and as run-off and/or drainage in irrigation.

On-farm irrigation management and practices play a crucial part in improving EA and reducing irrigation losses; but several factors need to be considered, mainly the quantity, the quality and the spatial and temporal distribution of water resources.[30] To begin with, water quality, as mentioned earlier, should be subject to strict management and regular monitoring. Furthermore, water quantity encompasses the selection of water efficient irrigation systems that could improve efficiency to 90%.[32] For instance, sprinkler systems with low pressure increase irrigation efficiency substantially under windy conditions.[41] In Montana (USA), Bauder[42] estimated that low-pressure sprinkler systems reduce average water losses by about 50% compared with high-pressure systems. We should not exclude precision agriculture as a practice, as it could reduce water use and improve farm economics considerably, and thereby subsequently contribute to the sustainability of agricultural production.[29,43] Indeed, computerised and GPS-based technologies enable farmers to control more precisely the spatial and temporal management of water application as provided by wireless sensor networks.

The implementation of well-managed deficit irrigation scheduling could contribute considerably to water savings and further improve farmers' benefits without compromising the yields.[44] Further, with scientific advances in physiology, new avenues in the improvement of deficit irrigation could be explored in the future.[45] In addition, irrigation scheduling requires not only the optimisation of water volume, but also the optimisation of irrigation timing. The interaction among wind velocity, temperature and humidity, changes the EA extensively. According to Bauder[42], EA might vary in sprinkler irrigation between 9% and 26%, depending on the wind velocity, the pressure of the system and the volume of water applied. Moreover, as seen in the semi-arid areas of Spain, by shifting irrigation from day to night, water loss from wind drift and evaporation losses in sprinkler solid-sets and moving laterals could be reduced by up to 50%.[46,47] This shift should be seriously considered in South Africa where it is common practice to irrigate with high-pressure sprinkler systems in the middle of windy days when wind drift and evaporation losses are extremely high.

Sustainability research

Sustainability falls within transformative research. The major concerns of this type of research are to solve fundamental problems in order to secure effective, equitable and durable solutions to agriculture and food production in a changing climate. These difficulties are increasing the pressure on our ecosystems and our societies.

To reach sustainable management of water resources in agriculture, an integrated approach should be applied, which combines the latest findings in crop research, agricultural practices and irrigation management. In this way, the most cost-efficient options that would alleviate environmental burdens can be chosen. El Chami and Daccache[48] have introduced a novel approach to implement sustainability assessment. It consists of the integration of crop growth models, life-cycle assessment models, general circulation models and economic models into one framework for application at farm level. The application of this approach could for example be to compare different drought-resistant varieties of the same crop, under different conservation practices and different irrigation schedules and techniques. This application would increase the options for farmers to optimise resource use while keeping income in mind.

Sustainability research could also focus on integrated modelling for large-scale regional optimisation, taking into account the regional water balance, climate change and land use.[49] Within this approach, the available natural resources (soil, water and air) could be optimised on a life-cycle basis. This modelling could also integrate water treatment and re-use within the regional water balance.

Conclusions

The NWRS2 has been briefly reviewed and a practical framework to follow for the sustainability of the agricultural water resources in South Africa has been presented. This framework would reduce water losses in agriculture, increase water use efficiency, and optimise the use of other natural resources (soil and air), which would benefit farmers. Governmental bodies play an essential role in water management in terms of designing, implementing and monitoring policies that promote sustainable management of national water resources for agricultural use (e.g. charges and taxes, incentives and penalties, as well as banking facilities for new and efficient systems). However, the focus here was on research in agriculture which should be adopted by universities in South Africa in collaboration with other research institutions, especially public policies that encourage funding research in sustainable and transformative science; such research should include[50,51]:

1. Strategic crop research, with a focus on resources and technologies to find new breeds and varieties that perform better under the local drought and heat conditions in order to improve water use efficiency without compromising yields.
2. Intensified research in agricultural practices, including ecological and conservational approaches to assess, for different local crops, the yields and water use efficiency of national agriculture.
3. Research on methods to increase the efficiency of water use within agriculture as an essential and strategic priority.
4. Integration of all of the above within a sustainable research framework at farm and large scales.

The dimensions of this roadmap are designed on a national level. However, for successful governance, regional stakeholders guided by these pillars are invited to design regional steps, which cover the specific needs of local communities. In parallel, the involvement of society should be increased by a participatory approach for an efficient governance. Societal involvement should be accompanied by media awareness campaigns to promote good practices and discourage conventional practices (e.g. soil burning and ploughing). Educational programmes at schools and universities, as well as educational messages (similar to promotional messages) on radio and television, could have high social impact. Extension services should also address scarcity issues explicitly through farmers' magazines, short courses and pilot projects, because recent research shows that farmers have weak incentives to increase farm efficiency through implementing new practices.[52]

Finally, this article is an urgent call for all stakeholders and policymakers in government bodies and in research institutions to accelerate the implementation of the roadmap. It might take years to obtain results, especially because agricultural practices take 2–3 years to establish, and crop research requires, in some cases, decades.

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Authors' contributions

D.E.C. wrote the first draft of the manuscript; M.E.M. made the revisions to the methodology section; both authors approved the final submission.

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