An assessment of sustainable maize production under different management and climate scenarios for smallholder agro-ecosystems in KwaZulu-Natal, South Africa

N.J. Walker *, R.E. Schulze

School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Private Bag X01, Scottsville 3209, South Africa

Abstract

The need to improve smallholder rainfed maize production in a sustainable manner is important in South Africa, as maize is a staple food to the rural indigenous population. Smallholder maize production is often characterised by low yields, which are often significantly lower than the potential for the land. However, sustainable maize production is not only a question of yields, but also of protection of the environmental resource base, social welfare, and the livelihoods of farmers as well as adjacent rural and urban communities. Sustainability for the smallholder farmer raises questions of household food security, farmer and community well-being as well as agro-ecosystem integrity.

Sustainability was assessed at the smallholder agro-ecosystem scale using a goal-orientated sustainability framework. The use of the physically based CERES-Maize crop model within the sustainability framework meant that agro-ecosystem responses to different management options (e.g. tillage systems and fertiliser application) and climate change scenarios could be quantified. The agro-ecosystem that has been simulated is at Potshini village, which is about 10 km from Bergville in the western-central region of KwaZulu-Natal province, South Africa. The agro-ecosystem was simulated for different management strategies for a range of plausible future climate scenarios for South Africa. The future climate scenarios of '2 °C' and '2 °C + 10%rain' had the biggest positive effect on mean grain yield. These scenarios had increases of over 1000 kg/ha with inorganic fertiliser and ~200 kg/ha with manure. The largest negative effects on yield are with the '+2 °C' scenario. The biggest increase in losses of organic nitrogen were with the '2 °C + 2 °C' scenario where losses increased by up to 5%.

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1. Sustainable smallholder agro-ecosystems

The population in sub-Saharan Africa is predicted to increase to over one billion by 2025 (Inocencio et al., 2003). In order to meet the food requirements of the increased population and achieve food security by 2015, agricultural production would need to increase by 6% per annum (Inocencio et al., 2003). These advances will need to be made with the added problem of predicted climate change. Climate change will potentially affect the lives of people in many ways, particularly in Africa where many poor smallholders depend on agriculture for their livelihood and where there are few alternatives of earning a living (Jones and Thornton, 2003).

The need to improve smallholder rainfed maize production in a sustainable manner is important in South Africa as maize is a staple food. Smallholder maize production is often characterised by low yields, which are often significantly lower than the potential for the land. Sustainable maize production is not only a question of achieving reasonable yields, but of government policy on agriculture, protection of the environmental resource base, social welfare, and the livelihoods of farmers and adjacent rural and urban communities. Sustainability for the small-scale farmer raises questions of equity, economic viability of
their operations and household food security. It is valuable to investigate sustainability at the field scale using both field data and model simulations for an improved understanding of food security at the household level. At the household level it is crucial for the farmer to minimise fluctuations in household income over time, as well as to maintain or increase a particular wealth level and nutritional status (Thornton and Wilkens, 1998). The small-scale farmer is more susceptible than commercial farmers to climate variability and its impact on yields.

The use of a systems approach is deemed essential in assessing agro-ecosystem sustainability and in understanding the inter-relationships between social, economic and environmental influences that are associated with sustainability (Ikerd, 1993; Hansen and Jones, 1996). In this assessment the following working definition of sustainability, based on the work of Chambers (1997), is used: ‘Sustainability is applying long-term perspectives, in regard to human well-being and ecological integrity, to policies and actions’. The definition of sustainability selected is central to the determination of types of agro-ecosystem functions used to assess sustainability. In regard to this paper, long term is considered to be two generations, or 40–50 years.

This length of time is useful as rainfall in South Africa has been identified by previous research (Tyson, 1986) as having 18–22 year ‘cycles’. The climate data set used included 49 years of data which ensured that the period to test sustainability covered at least two of these cycles. A goal-orientated framework was adapted from von Wiren-Lehr’s (2001) goal-orientated system. This framework has been devised to answer the following questions: How can an actual agro-ecosystem be identified as being sustainable or not? What facets of a system make it sustainable? Are there research and operational implications associated with climate change? Incorporating Hansen and Jones’ (1996) scheme to characterise sustainability, the adapted sustainability framework has the following four steps:

- Goal definition (define sustainability, spatial scales, state required framework outputs; ensure that the goal selected is one that is realistic to obtain).
- Sustainability modelling (select the simulation model and the model outputs to use as quantitative indicators of sustainability).
- Evaluation strategy (compare quantitative measures of different strategies to managing the system).

Fig. 1. Location of Bergville in KwaZulu-Natal, South Africa.
• Management advice (make recommendations that are predictive, with constraints to sustainability identified).

2. Objectives of the study

The objective of this assessment was to investigate sustainability at the smallholder agro-ecosystem level. Agro-ecosystem sustainability was assessed in regard to yield, soil organic carbon and nitrogen responses to a range of management practices and plausible climate scenarios. The following combinations were simulated:

(a) four tillage practices,
(b) two fertiliser practices and
(c) six climate scenarios.

An important aspect in regard to yield is what has been termed the famine level. The famine level has been calculated as ~900 kg/ha of maize which is the amount of grain required for a family of four to survive to the next harvest when cultivating an 1 ha plot (du Toit et al., 1999). Yield from the crop model simulations is compared against the famine figure.

3. Description of study area

The Bergville district of KwaZulu-Natal (Fig. 1) is an area where maize is produced by both large-scale commercial farmers and those emerging farmers who not only own smaller plots of land, but also have limited access to external inputs. Maize production forms part of the smallholders’ livelihood. Other work, if available, is often taken by the farmers and their families are also reliant on those in the family who are able to claim a state pension. Fieldwork has shown the majority of the small-scale farmers in the Bergville area to be women. This is true of small-scale agriculture in much of Africa, where 60–80% of the agricultural labour force is female (Williams, 1994). The small-scale farmers in the area generally have around 1 ha of land to farm and this is situated close to their homestead. The soils in the area are highly acidic. Extensive liming is therefore required to improve yields (Smith et al., 2004).

Although one of the local varieties of maize grown (landrace maize) has a high tolerance to acidic soils, liming is still required. The soil in the agro-ecosystem for which yields were simulated is an Avalon soil form which has a sandy loam soil texture with a thickness of 900 mm (Smith et al., 2004). Bergville is in South Africa’s summer (October–March) rainfall area and with rainfed agriculture the planting date for maize is around mid-November. The altitude for the site is 1150 m above sea-level and it has a mean annual precipitation (MAP) of 684 mm (Lynch, 2004). It has a potential evaporation of 1600 mm A-pan equivalent and a mean annual temperature of 13 °C (Schulze, 1997).

4. Modelling smallholder agro-ecosystems

In order to assess the sustainability of small-scale agro-ecosystems, the goal-orientated framework of von Wienen (2001), the four steps of which were outlined in the introduction, was employed. The steps in the adapted goal-orientated system are identifying the goal, sustainability modelling, evaluation and management advice. This study examined how the agro-ecosystem functions were affected by modifications to the environment. Any major changes, positive or negative, could have significant bearing on the long-term food security of the village of Potshini, where the agro-ecosystem was simulated. Potshini is about 10 km from the town of Bergville in the western-central region of KwaZulu-Natal province, South Africa.

The goal definition used for this assessment was as follows:

‘The goal is for smallholder agro-ecosystems in the Potshini area to continue in the long term, providing quality well-being for farmers and local communities and to maintain ecological integrity’.

For sustainability modelling in this assessment the CERES-Maize crop model was utilised. This crop model was chosen because it has received extensive regional calibration for southern Africa (du Toit et al., 1994, 1997) and because of its range of management options. The modifications made to CERES-Maize v3 for South African conditions were tested using a historical field trial, as well as commercial data in order to determine whether the adaptations were site specific. Outcomes from these tests established that the adapted CERES-Maize retained its portability for application elsewhere (Tsuji et al., 2002). The biophysical indicators chosen from the CERES-Maize crop model output provide quantitative information on how the agro-ecosystem responds to both management and environmental changes. The biophysical indicators used in this assessment were maize grain yield, soil organic carbon and soil organic nitrogen levels.

A range of management options was assessed. These options included four types of tillage practice (no till, rip, disc and shallow tine) in combination with applications of either inorganic fertiliser or manure. Because the CERES-Maize (Jones and Kiniry, 1986) model version 3.5 in its original form was unable to distinguish between effects of different tillage practices on evapotranspiration and root growth of crops (one of the important input options in the model’s soil file), du Toit et al. (2002) developed algorithms from extensive field tillage trials at Potchefstroom in South Africa to calculate the soil root growth factor at different soil depths for several tillage practices. The soil root growth factors were used to simulate yields from the four tillage practices which were compared with actual yields (du Toit et al., 2002).

A sensitivity analysis to present and plausible future climate conditions formed part of this study. To determine what would be ‘plausible’ in future, output from South Africa was analysed from the Conformal-Cubic
Atmospheric Model (C-CAM), a regional climate model developed by the CSIRO in Australia. C-CAM was validated for present climate conditions (1975–2005) and then applied for simulations of a 2070–2100 future climate over southern and tropical Africa by Engelbrecht (2005). Cognisant of the fact that climate change predictions suggest different temporal distributions of daily rainfall and temperature (e.g. Engelbrecht, 2005), a simple approach was adopted by considering 'plausible' rainfall changes from the present (i.e. $D_P$) at Potshini to range from $D_P = -10\%$ to $+10\%$ by linear change of present daily values and plausible temperature perturbations were taken to be $\Delta T = +1\, {^\circ}\text{C}$, $+2\, {^\circ}\text{C}$, $+3\, {^\circ}\text{C}$ compared with present daily values. In the sensitivity analysis for this study the following scenarios were evaluated with respect to their potential impacts on the agro-ecosystem:

- A doubling of pre-industrial CO$_2$ atmospheric concentrations from $\sim 280$ ppmv to 560 ppmv, i.e. the ‘$2 \times$ CO$_2$’ scenario: A $2 \times$ CO$_2$ scenario implies enhanced photosynthetic rates plus changes in stomatal conductance, with resultant reductions in transpiration rates. The hypothesis is that this scenario would increase yields, more so with higher plant densities than with lower ones.
- Increasing both minimum and maximum daily temperatures by $2\, {^\circ}\text{C}$: i.e. the ‘$+2\, {^\circ}\text{C}$’ scenario: An increase in temperature promotes rate of crop development but, simultaneously, through increased evaporative demand, can dry out soil more rapidly. An increase in the rate of development would reduce the time available for the crop to capture solar radiation and convert CO$_2$ to biomass. The hypothesis, in a southern African context in

Fig. 2. Mean of simulated grain yields over 49 seasons at Potshini under different management options and climate scenarios.

Fig. 3. Coefficient of variation of yield over 49 seasons at Potshini under different management options and climate scenarios.
which climates are rainfall limited but not radiation limited, is that yields would generally decrease with an increase in temperature by itself.

• The ‘2×CO₂ + 2 °C’ minimum and maximum daily temperature scenario: The hypothesis with the combination of effective doubling of atmospheric CO₂ concentration plus increased temperatures is that the ‘drivers’ in this climate change scenario are self-cancelling up to a point.

• The 2×CO₂ 10% reduction in rainfall scenario combines an effective doubling of atmospheric CO₂ with a 10% decrease in rainfall. Termed the ‘2×CO₂ – 10%rain’ reduction scenario, the hypothesis is that the drivers in this climate scenario will be once more self cancelling up to a point.

• A doubling of CO₂ concentrations in combination with a 10% increase in rainfall, i.e. the ‘2×CO₂ + 10%rain’ scenario, is hypothesised to increase not only yields, but also increase losses of soil organic nitrogen and carbon.

The different scenarios were modelled at Potshini over 49 seasons and modifications to the CERES-Maize input files were performed to mimic the different climate regimes. The daily rainfall data used were from a climate station situated in Bergville and the daily maximum and minimum temperatures were obtained from the gridded daily temperature database of the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal (Schulze and Maharaj, 2004).

5. Results

Four tillage options were modelled under six different climate scenarios (present plus five plausible future ones) in combination with both inorganic fertiliser and manure applications. The outputs from the CERES-Maize crop model which were selected to assess sustainability were mean grain yield (Figs. 2, 6 and 7), the coefficient of variation of yield (CV) shown in Fig. 3, loss of soil organic nitrogen (Fig. 4) and loss of soil organic carbon (Fig. 5). To test for stationarity, a trend analysis was performed with the Mann-Kendall non-parametric test (Suppiah and Hennessy, 1998) on crop yields under 49 years of present climatic conditions assuming adequate inorganic fertiliser application. The test showed no significant trend at the 99% confidence level.

The results in Fig. 2 show that the maize yields from those treatments in which inorganic fertiliser is applied, are approximately twice as high as those treatments using manure. Overall the differences in yield between the various tillage practices are small. This could be due to the algorithms not capturing the differences which have been observed to exist between the tillage practices. The biggest positive effects of the five future climate scenarios on mean grain yield are with ‘2×CO₂’ and ‘2×CO₂ + 10%rain’. The largest negative effects are with the ‘+2 °C’ scenario. The combination of ‘2×CO₂ + 2 °C’ gives more or less the same yields as present climate, with the positive effects of CO₂ fertilisation outweighing the negative effects of the 2 °C increase slightly. The hypotheses set out in the previous section regarding the effects on yield of the five future climate scenarios have therefore been borne out by the simulations.

The CVs of yield with those treatments using manure are approximately double that of the CVs for those treatments using inorganic nitrogen as the nitrogen input into the system (Fig. 3). Within a given tillage treatment with the addition inorganic fertiliser there is relatively little difference in variability from one climate scenario to the next. In regard to the future climate scenarios the biggest increases in variability of yields when using manure, com-
pared with present conditions, is ‘2 × CO₂’ and ‘2 × CO₂ + 10% rain’. For those treatments using inorganic fertiliser all the future climate scenarios modelled were found to reduce the variability when compared with the CV of maize yields under present climate conditions.

The losses of soil organic nitrogen from the agro-ecosystem over the 49 seasons simulated are higher with those treatments applying manure than with inorganic fertiliser (Fig. 4). With the exception of the ‘2 × CO₂ – 10% rain’ scenario all other future scenarios display higher soil organic nitrogen losses than under the present climate. The most striking increase in losses of organic nitrogen is with the ‘2 × CO₂ + 2 ºC’ scenario. This scenario is the most likely of the future scenarios as there are more uncertainties regarding future rainfall patterns than increases in CO₂ concentrations and temperature. The losses of soil organic carbon is, again, higher with the manure treatments than with those using inorganic nitrogen for a given tillage practice (Fig. 5). Again, with the exception of the ‘2 × CO₂ – 10% rain’ scenario, the other future scenarios all experience increased losses, with the ‘2 × CO₂ + 2 ºC’ scenario producing the highest of those losses.

A comparison of perennial yields for the ‘2 × CO₂ + 2 ºC’ climate scenario between treatments using inorganic fertiliser and manure reveals the difference in inter-annual variability of yield between the two treatments (Figs. 6 and 7). With the use of inorganic fertiliser at recommended levels the maize yields are less variable than with manure and, over time, do not fall below the famine level of 900 kg/ha.

The maize grain yields for the manure treatment are reducing over time (Fig. 7). This is true for all the climate scenarios modelled, including present climate. The use of manure with a nitrogen content of 67.8 kg N/ha (Lumsden 56.0 58.0 60.0 62.0 64.0 66.0 68.0 70.0 72.0 74.0 56.0 58.0 60.0 62.0 64.0 66.0 68.0 70.0 72.0 74.0 1 3 5 7 9 11 31 51 71 92 12 32 52 72 93 14 34 54 74 9 0 1000 2000 3000 4000 5000 6000 7000 8000 9000 1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 Seasons Present CO₂, 360 ppmv "Doubling" of CO₂ at 555 ppmv +2 ºC

Fig. 6. The influence of an effective doubling of CO₂ with a temperature increase of 2 ºC on maize yield with rip tillage, when using inorganic fertiliser.
and Schulze, 2004) over an extended period of time does not provide enough nitrogen for the crop. As a consequence, not only do yields reduce, but also the soil quality, due to increasing amounts of soil organic nitrogen and carbon being lost (Figs. 4 and 5). Under present day climate conditions yields dropped below the famine level in eight out of 49 seasons when using rip tillage with manure assuming present climatic conditions and 10 out of 49 seasons with the ‘2°C +2°C’ climate scenario.

The modelling results show that one way for smallholders to improve yields considerably would be the addition of inorganic nitrogen to the system. It was found that this management action would prevent the yield from falling below the famine level of 900 kg/ha in all years for the scenarios run and would, therefore, have a positive effect on household food security.

6. Discussion and conclusions

The author-defined goal for this assessment at a smallholder farm scale is: 'The goal is for smallholder agro-ecosystems in the Potshini area to continue in the long term, providing quality well-being for farmers and local communities and to maintain ecological integrity'. The results for all climate scenarios and for all tillage options show that the addition of inorganic fertiliser is required as an input in the system to sustain yields over the long term. Obstacles that could prevent the smallholder from using fertiliser rather than manure would be lack of access to credit and transport. Also, the decision to use capital to buy fertiliser might not be a current family priority. The fertiliser applied in the simulations was 120 kg/ha of inorganic nitrogen which is sufficient for maize production in the area and does not exceed recommended levels (Smith et al., 2004). The groundwater recharge at Potshini is relatively low (Schulze, 1997) coupled with the low intensity of agricultural production groundwater contamination is currently not a problem.

The Bergville area often experiences a mid-summer dry spell in January (Smith et al., 2004). The dry spell retards plant growth, and especially grain filling, and can therefore reduce maize grain yields quite markedly. This is perhaps where conservation tillage would be of advantage particularly to rain-fed maize production, as the soil under conservation tillage would preserve its moisture for longer and thus reduce the effects of the dry spell. The results from the CERES-Maize model do not show this, however. Yields from the conventional tillage type (disc) had the most favourable combination of yields and variability in yields under most of the climatic conditions modelled, including present climate conditions. This perhaps shows weaknesses in the version of the CERES-Maize model used when simulating conservation tillage effects and also in the algorithms used to calculate the soil growth root factor. Smallholder farmers (~1 ha field size) in the Potshini area have actually experienced an increase in yields when conservation tillage practices have been used on their land (Smith et al., 2004).

According to model results the different tillage practices did not give vastly different results. These results suggest that further verification of the tillage practice routines is needed. Under natural conditions the differences in tillage practices would be wider. The difference between yields simulated and those observed may be caused by a combination of factors. Tillage has a complex effect on maize. The algorithms developed by du Toit et al. (2002) account for some of these effects, but not all, particularly in regard to the beneficial effect of no till and the protection that a good mulch cover provides for the soil. Improved tillage routines need to be incorporated into the model so that tillage can be modelled successfully across a range of environments. This is an aspect which is currently being addressed by the CERES model developers.

The climate and soils in the Potshini area have the potential for smallholder farmers to produce yields in excess of 4 tonnes/ha when using inorganic fertiliser and
conservation tillage techniques. With sound farming practice some of the smallholder farmers are already on the way to becoming semi-commercial, i.e. they are producing a high yield on the small farms that they possess. The income could then be supplemented by off-farm employment. Sound farming practices would also reduce their vulnerability to climate change. This would need to be coupled with sound grazing management for cattle and goats. These measures would increase the ability of the agro-ecosystem to cope with climate related shocks and therefore increase the resilience of agro-ecosystem.

The responses of maize yield and soil organic nitrogen and carbon losses to the five plausible future climate scenarios were for the most part, as had been hypothesised. A temperature increase by itself was found in the simulation to reduce yields while a doubling of atmospheric CO₂ increased yields for all treatments modelled. It was hypothesised that with the ‘2 × CO₂ – 10% rain’ scenario the positive and negative drivers of changes in yield would be self cancelling, up to a point. All future scenarios with the exception of ‘+2 °C’ recorded an increase in yield when compared with those from present climate conditions. Of the plausible scenarios selected the ‘2 × CO₂ + 2 °C’ is considered the most likely future scenario to occur. In this study the future climate scenario ‘2 × CO₂ + 2 °C’ recorded the largest increases in losses of soil organic carbon and nitrogen for all the fertiliser and tillage treatments modelled.

Maize production under rain-fed conditions, however, still remains vulnerable to the adequacy, reliability and timeliness of rainfall. Farmers are averse to taking risks and investing in inputs and improvements, and this response results in low levels of productivity (Inocencio et al., 2003). Along with conservation tillage another management option which could be utilised in the Potshini area is rainwater harvesting. Rainwater harvesting is the process of conserving rainfall runoff in the field or in storage structures. This can help mitigate the effects of temporal and spatial variability of rainfall of the high risks of intra-seasonal dry spells (Inocencio et al., 2003). The use of this technology would also help alleviate the reduction in yields that a rise in temperature would bring.

References


Lumaden, T.G., Schulze, R.E., 2004. Application of Seasonal Climate Forecasts to Predict Regional Scale Yields in South Africa. IRRI/START, New York, USA.


