Towards ecologically sustainable crop production: A South African perspective

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ABSTRACT

Food production comes at an ecological cost, and the lack of sustainability of South Africa's crop production systems is becoming increasingly worrisome. While small scale emerging and homestead subsistence farming are significant in the agricultural sector, food production is dominated by large scale commercial agriculture. In this paper we analyse the ecological impact of South African commercial crop production and what can be done about it. Impact categories considered are divided into what we consider 'better-researched' problems: fresh water depletion, salinisation, soil degradation, eutrophication and land use change; and into what we consider 'emerging' problems for agriculture: greenhouse gas emissions, soil profile acidification, ecotoxicity and non-renewable resource consumption. While there is a paucity of quantitative information, it is clear that after decades of cultivation many of our agroecosystems are degraded or degrading. Sustainable crop production and food security are ‘wicked’ problems – containing dynamic social, economic and biophysical complexities. Increased stakeholder engagement to better understand these problems, the tradeoffs linked to finding solutions and to involve those with the resources to turn knowledge into action is required. Collecting key data, turning it into information within local contexts (involving the ecology, agronomy, sociology, psychology, economics and other disciplines simultaneously) and communicating it effectively to allow learning and adaptive management at various spatial and temporal scales is essential. An example is the display of river flows on a website in real-time to help farmers manage and adapt irrigation practices better, and to connect them with other stakeholders to improve understanding of the responsibilities of managing water at local and catchment scales.

Keywords: sustainable crop production, soil and water degradation, land use change, greenhouse gas emissions, salinization, resource depletion

Highlights:

- Review of ecological impact of South African commercial agriculture conducted
- It is clear that most of our cropping systems are degraded or degrading
- Sustainable crop production and food security are complex, dynamic challenges
- Part of solution involves turning monitoring data into information
- Involvement of stakeholders with resources to take action is essential

1. Introduction

Producing food is arguably the most important use of our natural resources. Since the Second World War, intensive, mechanised agriculture has been evolving, so many of the fields we continue to cultivate today have produced food under intensifying practices for more than 70 years. In 2005, 90% of all food calories and 80% of all food protein and fats were derived from croplands (Kastner et al. 2012). Unfortunately, these practices have resulted in salinization of irrigated fields, depletion of freshwater aquifers, degradation of ecosystems due to the export of harmful agrochemicals, soil profile acidification, net soil organic matter (SOM) decomposition, and general loss of soil quality and fertility. According to the United Nations, sustainability '…calls for a decent standard of living for everyone today without compromising the needs of future generations'. Based on this definition of 'sustainability', most of the world's crop production systems cannot be considered sustainable simply as a result of the wide range of impacts – both onsite and offsite – associated with crop production (Figure 1).

South Africa cultivates around 12–13% of its total area of 122 million ha. Just over 14 million ha is under commercial agriculture (approximately 40 000 farming units), a well-developed sector relying on a high degree of mechanisation and synthetic agrochemical use. There are around 1.3 million smallholder farmers in former homelands, with around 2.9 million households engaging primarily in agriculture at the subsistence level (DAFF, 2012), generally charactersised by low input – low production systems. Approximately 1.3 million ha of South Africa (1% of total 13% of cultivated land) is under irrigation (DAFF, 2012), compared to the global national average of irrigation covering 21% of arable land (http://www.fao.org/nr/water). Food insecurity remains widespread throughout South Africa affecting 25% of the population (Labadarios *et al.*, 2011), which is projected to increase from the present 50 million to 60 million by 2030 (United Nations, no date). This population is also becoming more affluent, placing ever greater pressures on the natural environment.

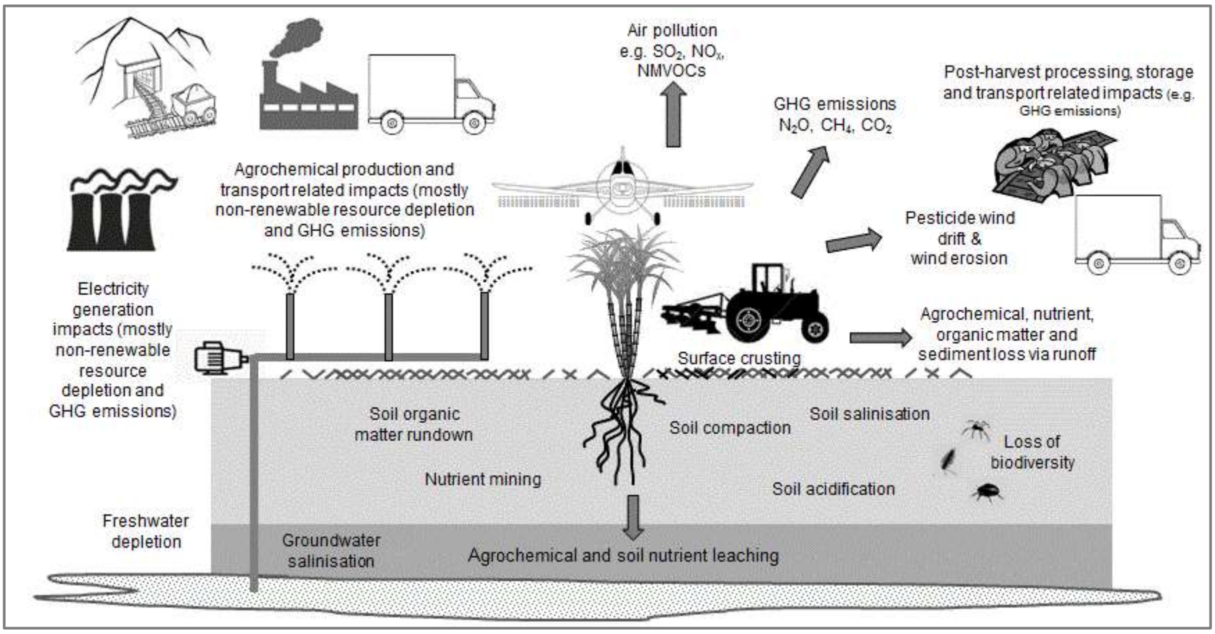

Figure 1 Schematic of impacts that crop production has or can have on the environment (GHG = greenhouse gas, SO_2 = sulphur dioxide, N_2O = nitrous oxide, NOx = nitrogen oxides, NMVOCs = non-methane volatile organic compounds, CH_4 = methane, CO_2 = carbon dioxide)

Feeding 9 billion people with the average diet from North America (USA and Canada) would require doubling crop land even if global yields were able to reach the current North American average (Kastner *et al.*, 2012). If no new land is to be brought into cultivation, this translates into a 2.4% yield increase per hectare per year for maize, rice, wheat and soybean, but yields for these crops are only increasing at 1.6%, 1.0%, 0.9% and 1.3% per year, respectively (Ray *et al.*, 2013). Food security is, however, not just about total food production, but also about a lack of access to food through the disempowerment of the world's poor (Loos *et al.*, 2014). More land will, therefore, continue to be converted to cropping unless circumstances and policies change to increase production per unit area and address the multiple variables that influence food security (Loos *et al.*, 2014). As we are already using the better agricultural land in most cases, conversion of poorer quality land will require greater input and management costs.

Climate change is an additional major new challenge. Counter-intuitively, the ratio of food energy outputs to energy inputs for our production systems has decreased greatly since the birth of mechanised agriculture and its reliance on fossil fuels. As an emitter of greenhouse gases (GHGs) and one of the sectors expected to be burdened most with the impacts of changing weather patterns, the agricultural sector is at the very centre of climate change.

Agriculture is also being recognised for the ecosystem services and multi-functional landscapes it can provide in addition to yield. These include biodiversity, natural habitats for conservation and recreation, climate stabilisation and aesthetic and cultural amenities such as vibrant farmscapes (Robertson *et al.*, 2014).

The aim of this paper is to analyse the ecological impact of South African crop production, with an emphasis on commerical agriculture (as opposed to small scale and homestead crop production) due to it being the major producer of food on the largest share of land, greater avaialibility of data and literature for this sector, and because it it perceived as having a greater impact due to its input-intensive nature. Problems are divided into what we consider 'well-described': fresh water depletion, salinisation, soil degradation, eutrophication and land use change; and what we consider ‘emerging’ problems for agriculture: greenhouse gas emissions, soil profile acidification, ecotoxicity and non-renewable resource consumption. For each problem area, approaches to reduce impact are also discussed.

2 Impact categories

2.1 Well-described problems

2.1.1 Fresh water depletion

The world’s population is projected to exceed nine billion by 2050, meaning that food production will need to increase by 70-100%, and irrigated agriculture will need to play a much greater role in achieving this goal. Globally, the water footprint of agriculture is estimated to be over 90% of Humanity’s total water footprint (Hoekstra and Mekonnen, 2012). Irrigation is estimated to use roughly 70% of the world’s freshwater withdrawals, supporting 30% of crop production yet accounting for only around 10% of total agricultural water use (Assouline *et al.*, 2015).

South African irrigated agriculture uses around 60% of the 13×10^9 m^3 runoff per annum used by all sectors, or just under 40% of the estimated 20×10^9 m^3 exploitable runoff (DWAF, 2004). Despite only 1% of the country’s surface area being under irrigation, it is responsible for 30% of agricultural production by value (Nieuwoudt *et al.*, 2004). As a result of increasing demands for water there is pressure to reduce irrigation and divert more water to industrial and domestic sectors. It is estimated that freshwater demand will exceed supply nationally by 2025 (Musvoto *et al.*, 2014), less than a decade from now.

Environmental flows, including low flow and high flow events, and estuary freshwater inflows are essential in maintaining healthy rivers and their surrounding terrestrial ecosystems that all society depends on. On the other hand, while the domestic and industrial sectors will need more water in future, these sectors will not use anywhere near the proportions of freshwater currently used by irrigation.

Freshwater depletion – finding and implementing solutions

One possible solution would be to link science, governance, community and/or industry around learning, in other words, connecting up the problem and solution spaces to address the worsening water situation. In the Crocodile River Catchment of South Africa, water resources are already fully allocated, and growing urban and rural populations, industry (including coal mining) and irrigation all have major impacts on the quantity and quality of river flows. For its final stretch through South Africa, the river flows along the southern border of the famous Kruger National Park, and then into neighbouring Mozambique. The environmental reserve for the Crocodile River is underpinned by scientific understanding and enshrined in South Africa's legal water governance framework. Monitoring is done by the Department of Water and Sanitation and current daily flows relative to the reserve plus predictions is shown live on a website (http://riverops.inkomaticma.co.za/). Information available to irrigators helps them to i) manage better, ii) adapt earlier and iii) through engagement with larger catchment scales understand why the reserve is there and why it is also in their long-term interest. The Inkomati Catchment Agency makes this information available to farmers to help them better manage their irrigation, but also to build consensus among the different stakeholders as to the size and quality of the resource they must share. So in this example, various stakeholders are being linked by real-time objective data to improve the management of water.

Only a tiny proportion of the world's wastewater is currently treated for reuse in irrigation. Between 680 and 960 million m^3 of domestic wastewater is estimated to be generated per day (an amount that will increase with population growth), with only 4% of this amount being treated to advanced levels (Lautze *et al.*, 2014). Reliable data on wastewater reuse in agriculture is lacking, but rough estimates indicate that about 20 million ha of agricultural land is irrigated with mostly untreated wastewater globally (Lautze *et al.*, 2014). While the human and environmental health hazards need to be considered, making better use of this resource for irrigation will be important in the future. In South Africa and other countries with a mining legacy, the opportunity to use poor quality mine waters, such as gypsiferous mine water from the Mpumalanga coal fields, to grow crops should be further explored. Monitoring from field to catchment scale will play an essential role to provide baseline information to manage the country's water more sustainably.

2.1.2 Salinisation

Salinity, often expressed as total dissolved salts (TDS) is classified as a non-toxic inorganic constituent, which may cause toxic effects at extreme concentrations (DWAF, 1996). Over one-third of the world's irrigated land is affected by salinisation and/or water logging (Singh, 2015). In South African waters, sodium, calcium, magnesium, chloride, sulphate and bicarbonate make up the major fraction of ionic constituents (Leske and Buckley, 2004). Elevated salt levels in surface water and groundwater are widespread and of national concern (DWA, 2011), but the country is relatively fortunate that the landscape enables leaching.

According to DWA (2011), 30% of river monitoring sites assessed in South Africa had unacceptably high salt levels (> 85 mS m^{-1}). A trend of increasing river salinity over time has been observed for the Crocodile River Catchment (Van der Laan *et al.*, 2012), and is largely attributed to irrigation activities (DWA, 2011). Van Niekerk *et al.* (2009) studied long-term salinity changes for 27 sites on major rivers over a 25 year period. Nine sites showed upward trends, eight showed downward trends and ten showed no significant change.

An estimated 1–12% of total irrigated area, depending on South African province, is severely water-logged or salt-affected, and 5-20% is moderately affected (Backeberg *et al.*, 1996; Commission, 1996; Le Roux *et al.*, 2007). In a study along the Lower Vaal River, Le Roux *et al.* (2007) observed that soils irrigated for more than 20 years with waters with EC ranging between 52–74 mS m^{-1} and a sodium adsorption ratio of <5 were not physically degraded, and that there was little to no effect on soil infiltration rates and saturated hydraulic conductivity.

Farmers located towards the bottom of catchments will in general receive poorer water quality as a result of upstream anthropogenic solute loading and natural geological weathering, as observed for the Crocodile River Catchment (Van der Laan *et al.*, 2012). This will require monitoring and where needed an adjustment of management practices, for example, the use of higher leaching fractions to ensure there is no accumulation of excess salts in the root zone. It is difficult to distinguish between river salt loads that have come from upstream irrigation and other anthropogenic processes versus those from natural weathering, and more work is required to better understand the source of river salinity. In coastal areas, discharge of irrigation return flows to tidal rivers that are already saline will likely have limited impact provided micro-elements, pesticides and other pollutants are below toxic concentrations. This is not the case further inland where irrigation return flows may require treatment before they are disposed of into evaporation lakes or into confined aquifers (Beltrán, 1999), which increases the cost of crop production.

Dryland salinity is an issue in the Western Cape, which has a Mediterranean climate with winter rainfall. Replacing deep-rooted indigenous vegetation with wheat has led to increased runoff and recharge, resulting in a shallow, saline water table (De Clercq *et al.*, 2010). The net salt discharge for the Sandspruit Catchment was estimated at 500 kg ha^{-1} a^{-1}, so these systems contribute significant levels of salt to the already salinized Berg River (De Clercq *et al.*, 2010). Worsening soil and/or water salinization over time causes yield reductions, increasing costs to farm and/or the need to remediate affected soils/landscapes, and ultimately loss of productive agricultural lands.

Salinisation - finding and implementing solutions

With technological advances, soil profile salinity monitoring – especially for perennial crops in which there is no regular soil disturbance – is becoming more feasible. Ceramic suction cups, wetting front detectors and automated electronic sensors can all be used for this purpose (Van der Laan *et al.*, 2011). As irrigators will be forced to use water of poorer quality over time, having access to real time soil water salinity data will be critical in monitoring their systems and guiding management practices, for example, determining the timing and size of leaching fractions (defined as the ratio of water that drains below the rootzone to that infiltrated into the soil surface).

As river salinity levels increase in many catchments, water resource managers will play an increasingly important role in setting goals or targets to ensure users are provided with water of appropriate quality. Resource managers can benefit from data on soil profile salinization, while irrigators will benefit from knowledge of changes to source water salinity to guide decision making. Again, monitoring data can bring different stakeholders together into the solution space, facilitate dialogue and understanding, and track changes which need to be managed communally.

In cases where irrigation returns unacceptable salt loads to the environment, these waters must be treated or disposed of (salt disposal ponds) and this expense must be factored into the cost of production.

2.1.3 Soil degradation

Soil organic matter (SOM) has a positive effect on soils and crop production, but southern Africa is generally characterised by low SOM levels as a result of the climate, with 58% of soils containing less than 5 g kg^{-1} soil organic carbon (SOC) (Barnard, 2000). Loss of SOM leads to reduced soil water holding capacity and infiltrability, and lowers overall fertility, including the supply of micronutrients (Snyman and Du Preez, 2005). Soil organic matter also plays an important role in reducing soil erosion through aggregate stabilisation, with erosion in turn being a major pathway of SOM loss. An estimated 100-363 million tonnes of soil is eroded annually in South Africa (Breetzke *et al.*, 2013). Lobe *et al.* (2001) observed a 65% loss of SOM after 34 years of cultivation for soils in the semi-arid South African savannah, noting that this is more than has been reported for soils in temperate and humid tropical climates. It was further noted that up to 50% of a soil's SOM can be lost after just three to four years of cultivation. Following 50 years of cropping a Hutton soil [Ferric Luvisol (FAO) / Alfisol (USDA)] in Pretoria, Nel *et al.* (1996) observed a 50% decline in SOM levels. Losses were less when appropriate nitrogen (N), phosphorus (P) and potassium fertiliser ratios were applied. Du Toit *et al.* (1994) found that 10-73% SOC and N was lost relative to native grassland following 5-90 years of cultivation of South African dryland soils. In a meta-analysis of published research studies on SOM and its indicator elements C and N for the southern African region, Swanepoel *et al.* (2016) observed that compared to adjacent uncultivated fields, crop production leads to an average 46% decline in SOM levels. Interestingly, Du Preez and Wiltshire (1997) observed that SOM levels could be increased under irrigation in arid areas, and attributed this to higher biomass turnover in these systems.

Using an average SOC level for cultivated land in southern Africa of 1.47% (±1.25%) and the average estimated SOC decline of 46% (Swanepoel *et al.*, 2016), the original SOC level can be estimated to be 2.72%. Assuming a soil depth of only 0.2 m, a bulk density of 1400 kg soil m^{-3}, and a SOM C:N ratio of 10, this means that 3.5 kg C m^{-2} has been lost, or 35 000 kg C ha^{-1} just from the top 0.2 m of soil. This also means that approximately 3500 kg N ha^{-1} has been mineralised into plant available ammonium (NH_4^+) or nitrate (NO_3^-), a significant source of N that was or could have been used by crops, or lost to the environment (see the *Eutrophication* and g*reenhouse gas emissions* sections below) if this source was not accounted for in the amount of fertiliser applied.

Mills and Fey (2003) reviewed the impact of land use changes in South Africa on SOM and surface crusting, and noted that loss of SOM from the top few centimetres of soil has a disproportionately large effect on soil infiltrability and nutrient supply. Surface horizon fertility is directly enriched by vegetation through litter returns and indirectly by trapping atmospheric dust and acting as a refuge for animals and birds (Mills and Fey, 2003). In climates where natural vegetation can survive all year, it is unnatural for soil surfaces to be bare, as often occurs after harvest or during fallowing in crop production systems. Exposing soils to raindrop impact also makes them more prone to crusting, and decreased aggregate stability due to surface clay dispersal can be linked to a decline in SOM (Mills and Fey, 2003). McIntyre (1958) observed that a 1 mm thick soil surface crust could reduce infiltration rate by a factor of 1800.

Soil degradation – finding and implementing solutions

There are still uncertainties regarding how to maintain or restore SOM levels in degraded soils (Du Preez *et al.*, 2011). Mills and Fey (2003) highlight the importance of N conservation and replenishment for retaining the all-important humus fraction to maintain soil quality. The existing low N fertiliser use efficiency values require that N fertiliser needs to be managed very carefully to benefit SOM levels without harming the environment.

Reduced or conservation tillage trials show that SOM levels can be maintained or increased through the adoption of particular cultivation practices, but restoring SOM levels is usually difficult and very slow (Du Preez *et al.*, 2011). In some cases this was achieved along with increased yield, but in other cases yields were the same or reduced (van Kessel *et al.*, 2013). It is estimated that only 60-70% of original SOM levels prior to cultivation are achievable through better management practices (Lal, 2008). As reviewed by Janzen (2006), sequestering C in soil is a ‘win-win’ situation because it removes CO_2 from the atmosphere while improving soil quality – and organic matter is also useful in crop production when it decays and provides nutrients to the plants. Janzen (2006) suggests first building up soil C levels, then seeking ways to optimize the time of decay, and finding ‘new ways of thinking about soil C dynamics, and tuning them for the services expected of our ecosystems’. Due to the complexity of interacting factors and the range of SOM types and quality, computer modelling has an important role to play in predicting the rate of decline or accumulation of SOM in different cropping systems that are subjected to different management practices (Mills and Fey, 2003). This needs to be complemented with data from long-term monitoring trials. Elemental isotope studies will play an important role here to improve our understanding of nutrient cycling and should be much more common when investigating N dynamics in agroecosystems.

2.1.4 Eutrophication

Eutrophication is a major problem in many agricultural regions around the world. In the United States, 70% of N and P delivered by the Mississippi River into the Gulf of Mexico is derived from agriculture (Alexander et al. 2008). Isermann (1990) calculated that agriculture was responsible for about 60% of the N and 25% of the P emissions into the North Sea. Agricultural runoff is also largely blamed for the degradation of the Great Barrier Reef in Australia (Brodie *et al.*, 2011).

According to Van Ginkel (2011), eutrophication is a major concern in a number of South African catchments. De Villiers and Thiart (2007) observed alarming and statistically significant increasing concentrations of dissolved phosphate at or nearing critical levels in approximately 60% of the major South African river catchments studied (1970-2005 data). The authors noted that the seasonal nature of river nutrient levels indicates that both point and non-point sources (NPS) are major contributors and that these nutrient fluxes equate to significant loss of fertiliser-equivalent nutrients. P levels are generally low in South African groundwater, but certain regions do contain groundwater that is NO_3^- enriched (Annandale and Du Preez, 2005).

Due to the diffuse nature of agricultural nutrient pollution it is extremely difficult to quantify. Despite the work that has been undertaken so far (Görgens), NPS pollution remains a major problem and needs much greater investment in research and incentives to improve farmer water and nutrient management. The ineffective management of sewerage in South Africa means that untreated or partially treated sewerage is often returned to waterways, and this is frequently the dominant source of N and P pollution. Informal settlements that do not have sanitation infrastructure can also contribute significant amounts of N and P to watercourses.

In intensive crop production, N fertilizer is often applied in excess of crop requirements to reduce the risk of N deficiencies occurring during the growing season (Stuart *et al.*, 2014). This, and a failure to account for N contributions made available through the mineralization of SOM, irrigation water and N biofixation leads to fertiliser N use efficiencies in the region of only 30 to 50% being commonly reported in the literature (Smil, 1999). Galloway *et al.* (2004) estimated that 20% of N fertiliser ends up in aquatic ecosystems. In less-intensive systems, such as dryland crop production, fertiliser N is frequently under-applied, resulting in a net 'mining' of soil N (Annandale and Du Preez, 2005). As irrigated systems are often characterized by higher nutrient application rates and excess irrigation, these systems are 'leakier' than most dryland cropping systems. From field scale nutrient balances, Annandale and Du Preez (2005) concluded that dryland crop production in South Africa generally has a limited impact on freshwater NO_3^- levels, especially when cropping takes place on deep soils. In addition to N losses via runoff and deep drainage, NH_3 volatilisation also leads to the eutrophication of ecosystems due to subsequent deposition of N, and N losses can be high when urea is applied, especially if surface applied.

Once in soil, inorganic P is relatively immobile as it adsorbs strongly to soil particles and organic matter. It is, therefore, generally accepted that the main pathway of P from cultivated fields to waterways is via surface runoff as soluble phosphate or attached to sediment. In addition to soil slope and surface conditions, runoff losses are influenced by timing and method of application, form of fertiliser used and tillage practice.

Since the early 1960s, there appears to have been a dramatic decline in N use efficiency (Figure 2) (http://faostat3.fao.org; http://www.fssa.org.za/Statistics.html, accessed 10 October 2015). This may in part be as a result of increased cropping frequency giving less time for N mineralisation, and/or a general decline in N mineralisation as a result of SOM decomposition. It is notable that South Africa has followed the same trend as the World average. The World figure has stabilised at approximately 23 tonnes of cereal per tonne of inorganic N fertiliser applied. If we assume a grain N content of 3%, this indicates an efficiency of around 70%, which is higher than often reported (Cameron *et al.*, 2013). Put differently, we would expect to produce at least 33 tonnes grain per tonne of N applied, so the value of 23 tonnes grain per tonne of N applied represents very innefficient systems. Of course it must be remembered that some of the N is applied to crops other than cereal crops and that organic fertilisers and N fixed by legumes are also used as a source of N for cereal crops, and these are not accounted for in the data in Figure 2. It must be remembered that the grain that is not marketed through formal channels is not included in the yield estimates.

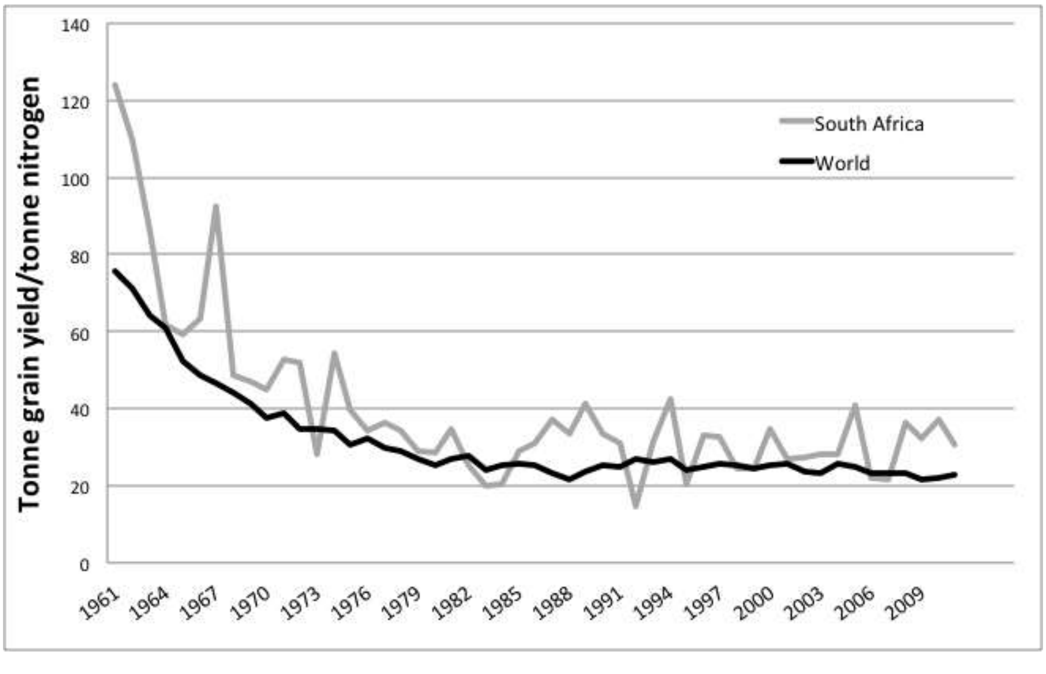

Figure 2 Cereal yield divided by nitrogen fertiliser consumption for South Africa and the world (http://faostat3.fao.org. http://www.fssa.org.za/Statistics.html, accessed 10 October 2015)

Eutrophication - finding and implementing solutions

Farmers are encouraged to match N and P supplied as fertiliser with crop demand as closely as possible, both temporally and spatially, to reduce nutrient export from cropped fields. Practical and economical challenges often make this difficult, resulting in some nutrient loss being inevitable. ‘Rotational diversity’ or ‘rotational complexity’ (Robertson *et al.*, 2014), which involves rotations with legumes and cover or catch crops can play a major role in reducing NO_3^- export from farmer fields. Cover crops scavenge nutrients from the soil profile, preventing leaching losses and making them available to subsequent crops through recycling. In some cases, but not always, including rotational complexity may come at the cost of short-term profitability. Multiple other benefits may result however, including decreased pressure from pests and diseases. Greater understanding is needed on who can and should carry these costs.

Some of the NO_3^- that has been exported from cultivated soils can be captured by adjacent riparian vegetation, or chemically altered streamside or in transit to more reduced forms of N, and wetlands can immobilise significant fractions as organic N (Robertson *et al.*, 2014). Restoring, maintaining and/or constructing wetlands, and the inclusion of appropriate buffer strips of natural vegetation between cultivated lands and fresh watercourses is important to reduce nutrient exports from cultivated land.

Switching from conventional tillage to minimum- or no-till can play an important role, primarily through improved nutrient cycling and the reduction of surface sediment, SOM and nutrient losses via surface runoff, but also because improved soil structure in no-till systems allows percolating water to move through via bypass flow avoiding equilibration with microsites which may have higher NO_3^- concentrations (Strudley et al., 2008; Robertson *et al.*, 2014). But such systems can also lead to increased deep drainage, so N fertiliser programmes need to be adjusted accordingly to prevent increased N leaching.

Under current practices, doubling food production is estimated to triple the current annual release of N and P to the environment (Tilman, 1999), and extraction of more water to increase production reduces assimilative capacity of water courses. A scientific effort comparable to that currrently undertaken for the global C cycle is required to understand the biogeochemistry of elevated quantities of N and P in our catchments (Tilman, 1999; Socolow, 1999).

2.1.5 Land use change

Humans have drastically changed the Earth's surface to meet our needs for food, feed, fibre, fuel and other requirements. Globally, humans have modified over 50% of ice-free land (Hooke *et al.*, 2012), with croplands and grasslands each covering 13%, tree-covered areas 28%, shrub-covered areas 9.5%, and artificial surfaces 1% (Smith *et al.*, 2015). Amongst other things, this has altered the surface energy balance, the C balance and the hydrological cycle. The latter has also been modified to provide freshwater for humans and irrigation, especially through the building of dams. Cultivated land has increased in South Africa from 3% in 1911, to 8% in 1980, to 12% in 1994 (Reyers, 2004). It has since then stabilised at this level. Of the total area of 122 million ha, 13.7% is estimated to be arable and 68.6% is estimated to be suitable for grazing (DAFF, 2012). Conserved land (excluding private reserves) covers 9.6% of South Africa's land surface area (DAFF, 2012), which is close to the commonly recommended 10 or 12% (Pressey *et al.*, 2003). Blanket recommendations such as these have inherent problems, such as not taking into account the biophysical heterogeneity of a region (Pressey *et al.*, 2003).

Generally, South African land use has been poorly planned, resulting in inefficiencies, inequities and environmental degradation (Reyers, 2004). DEA (2010) estimated that 70% of our agricultural land is degraded. Newby and Wessels (1997) postulated that 50–87% of the area used for grazing is degraded due to mismanagement. Arid regions are important as they harbour drought-resistant plant species (Darkoh, 2003). While the impacts of inappropriate land use in South Africa has been debated for centuries, it is usually only quantified in terms of soil erosion as opposed to more subtle indicators of quality in the soil that remains (Mills and Fey, 2003).

Biodiversity refers to the 'variety and variability among living organisms and ecological complexes in which they occur' (Darkoh, 2003). Biodiversity is vital for its role in habitat provision, soil conservation and productivity, waste assimilation, pollutant detoxification, pollination of crops and other vegetation, the control of agricultural pests, the dispersal of seeds and the transport of nutrients (Darkoh, 2003). Our current agricultural practices have led to declines in biodiversity primarily due to loss, modification, fragmentation of landscapes and their habitats and soil and water degradation (Foley *et al.*, 2005). Increased agricultural intensity also results in increased pressure on biodiversity and this is expected to continue into the future (Tilman *et al.*, 2001).

In the Cape Floristic Region (where most of the work on biodiversity has been done from a South African perspective), almost 9000 plant species (70% endemic) can be found in just 90 000 km^2 as a result of the region's transition from subtropical summer rainfall to temperate winter rainfall, as well as varied topography (Darkoh, 2003). In addition to the 25.9% of the region that has already been transformed due to agriculture and forestry (urban areas cover 1.6%), Rouget *et al.* (2003) estimate that over 30% of currently remaining natural vegetation in the Cape Floristic Region is under threat from further transformation by as early as 2023.

Land-use change – finding and implementing solutions

'Wildlife friendly farming' can include retention of natural habitat patches, extensively farmed semi-natural habitats and using management practices that reduce potential negative impacts of chemicals on non-target species, but has been criticised in Europe for its lack of success (Mattison and Norris, 2005). Ecologists, agriculturalists, social scientists and communities have the challenge of identifying priority areas, based on biodiversity and threat of land use change, for protection, and also of identifying appropriate cultivated land management strategies that are effective in conserving biodiversity. Perhaps this will see an increase in professionals describing themselves as 'agro-ecologists'. The links between biodiversity, land use and the drivers that shape land use must also be better understood (Mattison and

Norris, 2005). According to the authors, markets, policy, technology and the natural environment are the drivers that influence farmers' attitudes and circumstances, which in turn impacts on land use and biodiversity. Using camera-trap surveys in the Drakenbserg Midlands of South Africa, Ramesh and Downs (2015) observed the importance of available forest and wetlands to terestrial mammal biodiversity. The use of pesticides had a negative impact on the detection of several mammals, while some mammals appeared to be tolerant of human-modified habitats for agriculture.

2.2 Emerging problems

2.2.1 Greenhouse gas emissions

On a global scale, agricultural lands occupy 40–50% of the Earth's land surface and are estimated to account for 10–12% of total anthropogenic GHG emissions, including approximately 60% of the nitrous oxide (N_2O) and 50% of the methane (CH_4) (IPCC, 2006). If the complete life cycle of agricultural products is considered, agriculture's footprint rises to 26-36% of the global anthropogenic footprint (Barker, 2007). According to West *et al.* (2014), wheat, maize and rice are responsible for 68% of global N_2O emissions from cropland, and China, India and the United States contribute 56% of these emissions. Production of N fertiliser using the energy intensive Haber-Bosch process has a large C footprint. Nitrogen fertiliser application to soil can lead to significant emissions of N_2O, one of the three most important GHGs driving climate change, with feedback implications on catchment hydrology, crop growth and yield. Except in the case of newly limed or irrigated land the potential for C sequestration into SOM is low for cropland that has not undergone a land use change for the past 20 years, as any increases in biomass are assumed to be equal to losses from harvest and mortality (IPCC, 2006).

Agricultural GHG emissions have been estimated on a national scale for South Africa (Otter *et al.*, 2010), but these are mostly based on International Panel on Climate Change (IPCC) Tier 1 estimates, relying on crude regional emission factors and coefficients. A review of the literature indicates that no N_2O emission measurements have been published for cultivated soils in South Africa. Using modelling, van der Laan *et al.* (2015) estimated that N_2O emissions in a burnt, irrigated sugarcane cropping system ranged from 0.05-1.1% of applied fertiliser N. For an IPCC Tier 1 estimate of N_2O emissions from fertiliser applications, an emission factor of 0.01 kg N_2O-N per kg fertilizer N (1%) is recommended, which would have resulted in a slight overestimation relative to the modelling exercise. Emissions associated with fertiliser production, storage and transport accounted for 41% of total CO_2 equivalent emissions. The generation of electricity for irrigation of sugarcane was estimated to contribute approximately 25% of CO_2 equivalent emissions (van der Laan *et al.*, 2015). The simulations of van der Laan *et al.* (2015) also demonstrated that more judicious use of water and N fertiliser in irrigated sugarcane could reduce GHG emissions by 25% and non-renewable energy consumption by 20%, while achieving equal or even slightly higher yields.

The South African government is also implementing policy that will result in ‘feeding some of our food to our cars’, although the possibility of growing biofuel crops to reduce reliance on fossil fuels and GHG emissions and to improve rural livelihoods is certainly attractive. Stephenson *et al.* (2010) used life cycle assessment to show that producing biodiesel on already cultivated land where irrigation is not required reduced global warming potential by 20–36%. Conversely, farming new lands and using irrigation could result in a global warming potential significantly higher than that of South African fossil-based diesel. This study only considered limited impact categories, and the environmental burden of agriculture and fossil fuel in terms of eutrophication, aquatic and terrestrial acidification, ecotoxicity, salinity and other impacts would also need to be considered to enable a true comparison of the benefits currently being claimed. In a food insecure country that is a net importer of wheat and soybean, the how, what and where of growing food crops for biofuel production needs careful thought.

Greenhouse gas emissions – finding and implementing solutions

The growth of the middle class and changing food preferences is resulting in increased meat consumption in South Africa and globally. From Figure 3, it is clear that livestock production makes a much bigger contribution to GHG emissions relative to other agricultural sectors. If we can eat more crop produce rather than ‘feeding our food to our cows’, this could reduce our C footprint, and general environmental impact, substantially. This suggests that initiatives such as ‘Meat Free Mondays’ may have far greater potential to reduce South African agriculture’s C footprint than any current in-field mitigation measures in crop cultivation.

While the adoption of reduced tillage systems has the potential to increase C sequestration in soils, N_2O emissions for these systems may increase due to increased occurrence of anaerobic conditions resulting from reduced evaporation due to the mulch layer, together with a potentially larger labile C source for microbial decomposition (Eustice *et al.*, 2011). These two conditions are required for N_2O production and because this GHG is 210 times more potent than CO_2, this can result in reduced tillage counter intuitively having a larger C footprint. These measurements are difficult and require specialised analytical equipment. In cases where facilities, do not exist, collaboration with institutions that do have this capacity is needed.

Finally, if harvested biomass is used to produce energy it can reduce the carbon footprint of our agro-ecosystems, but should not come at the cost of replacing existing vegetation (Robertson *et al.*, 2014) or building-up of soil organic matter levels.

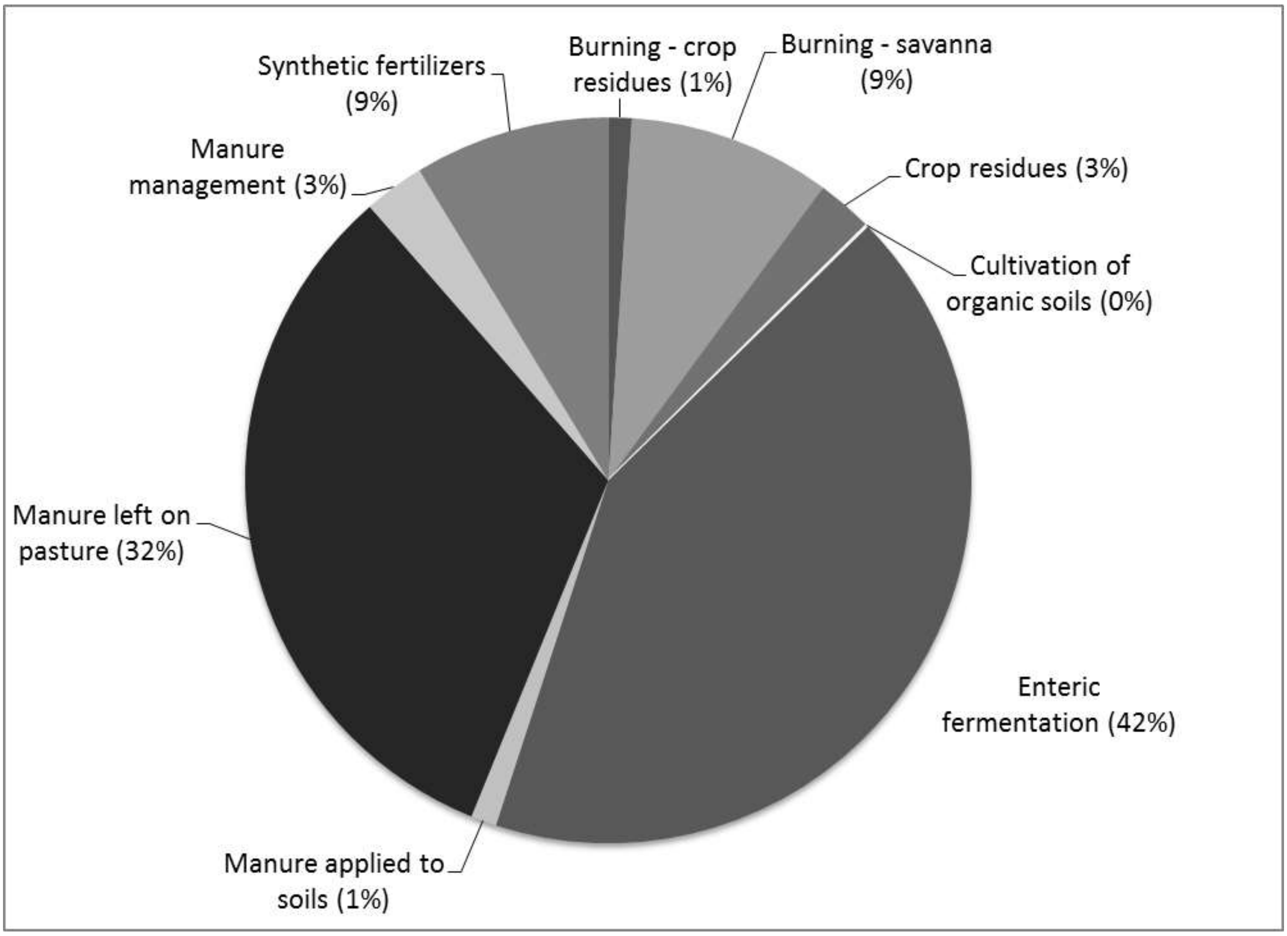

Figure 3 Relative contributions of different South Africa agricultural sectors to greenhouse gas emissions (from FAOSTAT - http://faostat3.fao.org/browse/area/202/E)

2.2.2 Soil profile acidification

Soil acidification is a natural process in temperate climatic conditions where deep drainage leaches basic cations, but can be accelerated through certain cultivation practices. Anthropogenic acid deposition can also lead to terestrial acidification, however, the focus here is on crop cultivation practices that lead to profile acidificaiton. The application of NH_4^+-based fertilisers can result in soil acidification when NH_4^+ is converted to nitrate NO_3^-, and when this NO_3^- is leached. The continued removal of cations in harvested plant material without equal returns back to the soil via amendments also leads to soil acidification.

While the impact of crop production on soil acidification is well known, few data are available for acidification trends at large spatial and temporal scales. In the rainfed regions of the South African sugar industry, decreasing soil pH has been observed with a decline in average industry pH (H_2O) from 6.2 in 1980–82 to 5.6 in 1996–1997 (Meyer *et al.*, 1998). This decrease seems to have been slowed and in some places halted in recent years, perhaps as a result of higher lime applications. Evidence of widespread subsoil acidity, however, remains a major concern as it is more difficult to fix (van der Laan and Miles, 2011).

Soil profile acidification – finding and implementing solutions

Sampling and monitoring topsoil as well as subsoil pH trends is important. Soil acidification can be addressed through adding agricultural amendments, particularly lime. Retention of crop residues has also been shown to increase soil pH (Butterly *et al.*, 2013), and this will be increased through the adoption of conservation tillage practices.

From a monitoring perspective, consolidating state as well as commercial laboratory databases to analyse acidification trends in different cropping regions will enable development of appropriate mitigation and maintenance strategies.

2.2.3 Ecotoxicity

Between 1960 and 2000, worldwide pesticide use increased by an average of 11% annually (Kookana and Simpson, 2000). There are over 3000 pesticide products (including insecticides and herbicides) approved for use in South Africa (DAFF, 2010), and a huge knowledge gap exists regarding the fate of these pesticides in the environment. This is mostly a result of the high costs involved in analysing for these compounds and the daughter break-down products which can also be toxic. In the registration of many agrochemicals in South Africa and consideration of safety issues, data from developed countries is most often utilised. Kookana and Simpson (2000) noted that herbicides have been observed to dissipate faster in tropical or sub-tropical environments than temperate ones, so data from one region may not be applicable to another.

In addition to conventional agriculture, golf courses, leakage from storage sites, washing of spraying equipment as well as atmospheric deposition and roof-wash off can be considerable sources of pesticide pollution (Jovanovic *et al.*, 2012). Many studies indicate that transport via runoff is the dominant flow pathway, with pesticide loads in subsurface waters much lower than in surface runoff, often by an order of magnitude (Kladivko *et al.*, 2001; Jovanovic *et al.*, 2012). Preferential flow pathways such as root channels and earthworm burrows can, however, lead to high rates of leaching, however. Shallow water tables may also increase contamination risk due to reduced travel distance. Pesticides are transported as solutes or with soil particles or organic matter. Aerial drift and volatilisation are also important transport pathways for pesticide pollution. Time between application and the first heavy rainfall event, slope, soil type, quantity of applied pesticide and its chemical nature, weather conditions, the presence, size and characteristics of buffer strips and erosion rills are major factors influencing the amount of pesticide that reaches freshwater systems (Merkle and Bovey, 1974; Cole *et al.*, 1997; Dabrowski *et al.*, 2002; Jovanovic *et al.*, 2012). These traits make this type of pollution highly site-specific.

Dabrowski *et al.* (2002) studied pesticide contamination in the Lourens River and its tributaries which runs through natural fynbos, intensive forestry and farming areas (orchards and vineyards). Chlorpyrifos was detected at a relatively high concentration in suspended solids in the main river, exceeding the No Observed Effect Concentration (NOEC) value calculated by Van den Brink *et al.* (1996). Azinphos-methyl could be detected six weeks after the last application in water and suspended sediments, at levels only slightly below concentrations acutely toxic to *Daphnia magna* and exceeding the 96-h lethal concentration 50 (LC50) of 0.37 μg L^{-1} for the midge *Chironomus tentans*. Endosulfan levels exceeded the proposed water quality limit of 0.01 μg L^{-1}, including the Acute Effect Level of 0.02 μg L^{-1} (DWAF, 1996). A number of other local studies have linked pesticide contamination with toxic effects in terrestrial and aquatic environments (Schulz *et al.*, 2002; Schulz, 2003; Bollmohr and Schulz, 2009). While limited, these South African data show that pesticides are in our water systems at harmful concentrations.

Increasing trends in the adoption of conservation agriculture (characterised by minimal soil disturbance, permanent soil cover and crop rotations) locally, while potentially beneficial to soil quality, may intensify dependence on pesticides, especially broadleaf herbicides. It has been estimated that in 2008-2009, 368 000 ha were under conservation agriculture in South Africa, representing 2.4% of cropped area (Jat *et al.*, 2013). This number has most likely increased at a very rapid rate over subsequent years, as evidenced by the increased sale in no-till planters (Dr Andre Nel, personal communication). It is also important to note that tillage practice can significantly affect pesticide behaviour in soil. High organic matter content favours improved soil structure, water retention and greater microbial activity, and reduced tillage generally decreases runoff and erosion losses (Kookana and Simpson, 2000). Due to increased pesticide use and the prevalence of macropores in these conservation agriculture systems, concerns exist that this presents a relatively greater pollution threat to aquifers (Golabi *et al.*, 1995), but the literature is inconclusive on this subject (Shipitalo *et al.*, 2000). The numerous benefits of conservation agriculture probably outweigh the disadvantages.

The wastewater from crop processing plants is often very rich in organic material. For example, 1.5 ML of wastewater containing 15% soluble solids and 30% pulp is produced for every ton of processed fruit pulp for canned or packaged juice (Burton *et al.*, 2007). This wastewater is toxic to microorganisms and livestock due to the high concentration of organics such as terpene-containing oils and flavonoids. The high carbohydrate content also results in a high chemical and biological oxygen demand (Burton *et al.*, 2007). Ideally some form of treatment or value-add is required before these wastewaters are disposed into our soils or water systems. For example, these waters could be re-assimilated into the irrigation water, although there are legislated limitations for how much of this water can be used for irrigation in South Africa.

Ecotoxicity - finding and implementing solutions

Despite the cost, there is an urgent need for more studies on the transport and fate of pollutants, especially pesticides, commonly used in our crop production systems. Advances in technology such as super critical fluid extraction and immuno-assays may assist in reducing costs and improve the speed of analysis of these types of compounds (Kookana and Simpson, 2000), enabling intensified research.

On the development side, effective pesticides that degrade quickly in the environment must be favoured. And mandatory use of appropriate buffer strips of natural vegetation between cultivated lands and fresh watercourses must be enforced.

Landscape diversity can be key for biocontrol and reduced pesticide usage. For example, the presence of heterogenous landscapes within 1.5 km of a soybean field was observed to strongly correlate with aphid suppression by lady bird beetles (Coleoptera: Coccinellidae) in the United States (Robertson *et al.*, 2014).

While the use of genetically modified (GM) crops has received mixed reactions, in addition to potentially achieving higher yield per unit area, the environmental benefits of reduced pesticide sprays are massively attractive. It has been estimated that the use of GM soybean, canola, cotton and maize reduced global pesticide use by 22.3

million kg of formulated product in the year 2000 (Phipps and Park, 2002). Locally, switching to GM Bt cotton with a degree of resistance to cotton bollworm complex (Lepidoptera) had a reduced impact on the environment due to less pesticide being used relative to non-Bt cotton in the Makhathini Flats (Morse *et al.*, 2006). Another potential benefit in the form of less exposure to pesticides for agricultural workers also exists. More research on this topic is required, and public awareness of the advantages and disadvantages needs to be improved.

2.2.4 Non-renewable resource depletion

As the ‘electricity-mix’ in South Africa is mostly coal based, electricity used for irrigation is produced using non-renewable fossil fuels. The same applies for all other crop production inputs, including urea, which requires around 68 MJ kg^{-1} (Bhat *et al.*, 1994) and the active ingredients of pesticides, which require around 120 MJ kg^{-1} (Mashoko *et al.*, 2010).

Phosphorus rock is a finite resource, and while details of reserves are politically and commercially sensitive, at the current rate of use, P rock reserves will most likely be exhausted in a hundred to some few hundreds of years (Dawson and Hilton, 2011). Reserves will also become increasingly costly to mine. As noted by Dawson and Hilton (2011), there is often government legislation to limit this nutrient’s impact on natural ecosystems, but no regulations requiring the efficient use and reuse of this non-renewable resource exist. Phosphorus fertiliser may in many cases have been over-applied in the past when energy costs were low, potentially leading to eutrophication and associated environmental impacts.

Non-renewable resource depletion – finding and implementing solutions

West *et al.* (2014) estimated that for 17 major crops studied, approximately 60% of N and 48% of phosphorus is applied in excess. While food production doubled over 35 years between 1961 and 1996, nitrogen use increased 6.87 fold and phosphorus increased 3.48 fold (Tilman, 1999). Recommendations under the 'Eutrophication' category will apply here too.

The use of sustainable biofuel and renewable energy in the place of fossil fuels will naturally have a big impact on limiting the use of non-renewable resources as well as pollution.

Better management of waste streams requires that agricultural by-products should be recycled wherever possible. Petroleum based plastics should be avoided in agriculture or replaced with biodegradable products. For the production of biofuel from agriculture, perhaps the use of different waste streams should be considered more carefully to reduce reliance on using agricultural land, particularly converting new fields, for the production of biofuel crops.

3. Discussion

The issue of sustainable crop production is multi-faceted and extremely complex, and problems can be either external or unfold on farm over the long term. Yield is a product of genotype (G) × management (M) × environment (E). Signifiant gains in G by plant breeders over past decades have masked the decline of E, which has also been neglected due to lack of consideration of "externalities", because impacts play out over a long time, and because it is extrememly difficult to quantify the economic cost of environmental degradation. Degrading E, together with stagnation in G, will present an ever-increasing challenge in many growing regions around the world. Significant regional gains can, however, still be achieved through plant breeding programmes in developing countries by adoption of improved M, including better use of water and fertilizers (Tilman, 1999). Current yields are estimated to be 50% below realistically attainable yields in parts of the world (West *et al.*, 2014), allowing much scope for improvement through better M. A major concern for South Africa and similar countries with well-developed commercial agricultural sectors but limited arable land is that crop production has already been largely optimised, leaving little room for improvement of yields.

But sustainable crop production and food security are 'wicked problems' – dynamically complex, influenced by many dynamic social and political factors as well as biophysical complexities, and for which the causes and effects are difficult to identify and model (Batie, 2008). For example, yield gaps may exist due to external factors such as poor transport and market infrastructure, making the risks of investment for improvements high (Godfray *et al.*, 2010). Often there is no clear consensus between different stakeholders on what the problem is, or the potential trade-offs required, and indentifying solutions is not just a scientific endevour but also a social and political process (Batie, 2008). For such wicked problems, greater levels of stakeholder engagement and involvement is recognised as key to: (1) better understand the cause and effect mechanisms, (2) interact with those whose resources and cooperation are essential for tackling the problem, (3) negotiate trade-offs and who bears the costs/gains, and (4) turning knowledge into action (Van

Bueren *et al.*, 2003; Batie, 2008; Weber and Khademian, 2008). In addressing sustainable crop production, increased involvement in research projects by other disciplines including sociology, psychology, economics and decision and political science must become routine. South Africa, as with many other countries faces a skills shortage, and leaders who are able to incorporate and integrate the knowledge, skills, resources and perspectives from many actors is needed (Ingram and Bradley, 2006).

Even from a linear science aspect, the problem is that we do not always know how to improve yield or sustainability (or even more challenging, both at the same time) as we are operating with too little information. Monitoring and documenting changes that have occurred from past activities are essential for improving systems understanding (Corwin, 2006). At larger scales it is essential not only for regional management, but also for community education about ecosystem functioning. At smaller scales, such as in-field, monitoring can be linked to actual management actions. Modelling can complement monitoring by providing 'glimpses into the future and insights into the causes of changes detected by monitoring' (Corwin, 2006), and enable exploration of 'what if' scenarios' (which can also be very useful in stakeholder engagement and negotiation). Monitoring programmes require long-term vision, appropriate legislation and funding incentives from government.

Best management practices (BMPs) have helped inform farmers how to manage better, but they have not encouraged or facilitated learning and adaptive management, and their effectiveness is well below expectation (Gleeson *et al.*, 2012). Adaptive management refers to 'a systematic process for continually improving management policies and practices by learning from the outcomes of implemented management strategies' (Pahl-Wostl, 2007) or 'learning to manage by managing to learn' (Bormann *et al.*, 1994). Gleeson *et al.* (2012) highlight the importance of setting sustainability goals/thresholds (for example, specific groundwater levels over multigenerational time horizons) instead of just establishing BMPs. Setting sustainability goals or thresholds will most likely be easier for water systems than for soil systems – the latter are more complex and currently less well understood. Greater effort therefore needs to be invested in developing key targets for soils.

Part of the solution may be reducing the homogenization of ecosystems that agriculture has caused (Tilman, 1999; Tittonell and Giller, 2013). Making use of rotational complexity, for example, to improve soil fertility and suppress pests and pathogens will potentially result in big improvements (Robertson *et al.*, 2014). The benefits of land sharing versus land sparing need to be carefully considered on a context-specific basis. For the latter, precision agriculture uses advanced technology to apply the right amount of water, nutrients and agrochemicals at the right place and at the right time. This reduces the inputs required and potentially the environmental damage, while increasing crop production and farm profitability.

4. Conclusions

Over a range of impact categories, it is clear that South African production systems are degraded or degrading. Farming continually degrading systems when increased yields are required to meet population growth is extremely worrisome. Due to increased globalisation, the impact of agriculture on the environment as a polluting and resource depleting activity is shared among all nations.

Scientists need monitoring data and modelling to figure out the ‘how’, but as importantly monitoring data needs to be interpreted and communicated in a way that can guide adaptive management, policy formulation and monetary investment. Addressing both immdediate food security and long term environmental sustainability simultaneoulsy is a wicked problem requiring greater engagement and action by all stakeholders.

Mitigating impacts will sometimes come at the cost of short-term farm profitability. In such cases, incentives for farmers will be required to ensure reliability of food supply. Ultimately society will need to pay for this, so the question becomes do we pay more for our food so farmers look after the environment better, or will we pay higher taxes so government can pay farmers for their stewardship of landscapes on behalf of society?

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