Formulating Crop Management Options for Africa's Drought-Prone Regions: Taking Account of Rainfall Risk Using Modeling

J. Dimes

Abstract Few smallholder farmers in Africa's extensive semi-arid regions use fertilizer and virtually none use recommended high levels of application. Essentially, Africa's farmers have ignored the formal fertilizer recommendations of national research and extension systems. Because of this, productivity gains from fertilizer use remain grossly under-exploited. The existing fertilizer recommendations are one clear example of an information constraint that has proven intractable, despite more than 15 years of farmer participatory research in Africa. Due largely to training, researchers are generally preoccupied with identifying and reporting only the best option – the near-maximum yield result. While such optima may be correct from an agro-climatic perspective, in drought-prone regions, the risk associated with seasonal rainfall variations can determine whether or not farmers are likely to adopt a new technology and in what form. Yet, almost no research and extension recommendations given to farmers in Africa include any estimates of the variability in technology response that can be expected due to climatic risk. ICRISAT and partners have been pursuing a range of improved crop management options for the semi-arid tropics through crop systems simulation and farmer participatory research. This chapter presents some examples of how the application of crop modeling can provide a cost-effective pathway to formulation of crop management options under variable rainfall conditions and for farmers with a range of resource constraints. It includes examples of fertilizer recommendations, crop cultivar selection, and residue management in semi-arid regions.

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Introduction

> It has long been recognized that blanket recommendations for fertilizer use are inadequate – although progress on addressing this issue has been painfully and unnecessarily slow.
>
> Malcolm Blackie, Malawi, 1994.

Few smallholder farmers in Africa's extensive semi-arid regions use fertilizer and almost none use recommended high levels of application (see Chapter "Micro-dosing as a Pathway to Africa's Green Revolution: Evidence from Broad-Scale On-Farm Trials" this volume). Essentially, Africa's farmers in these regions have ignored the formal fertilizer recommendations of national research and extension systems. Partly because of this, productivity gains from fertilizer use remain grossly under-exploited in Africa. Inappropriate fertilizer recommendations for resource-poor farmers are one clear example of an information constraint that has proven intractable, as highlighted in the Blackie statement above. Alarmingly, this statement is still largely applicable more than a decade on, particularly in regard to semi-arid cropping regions. The problem obviously is not only inappropriate blanket recommendations. A more fundamental issue is the methods and process used by researchers and extension agents to pursue such outcomes in the first place, and, despite more than a decade of participatory research initiatives, to persist with them in the second.

Part of the problem is that on-farm participatory experiments tend to yield highly variable season-

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and management-specific results that are difficult to interpret and draw conclusions from, while on-station research tends to give atypical results that reflect high levels of management and soil fertility. Overriding these technical constraints, and largely as a consequence of training, researchers are generally preoccupied with identifying and reporting only the best option – the near-maximum yield or economically "optimal" result. In the process, the smallholder farmer's reality of having limited resources with respect to the technology input, as well as competitive demands for these resources, is overlooked, as is the fact that the highest marginal returns are at the lower input levels on the response curve.

In developed world agriculture, it has been shown that the two risk-related factors with greatest impact on adoption decision are risk aversion and relative riskiness of a technology (Abadi Ghadim, 2000, described in Marra et al., 2003). Hence, it is reasonable to assume that resource-poor, strongly risk-averse farmers in Africa will be most interested in technologies that have limited risk and offer the highest payoff to input of limited resources. They will also tend to prefer technologies and management practices that constitute incremental changes in current farming practices and be willing to accept incremental rather than optimal benefits in productivity because of lower risk (Ahmed et al., 1997). Research and extension recommendations provide little advice on how to manage the necessary trade-offs associated with technology investment choices (e.g., Dimes et al., 2003) and say even less about associated risks – be it climatic risk, market risk, pest risk, or information risk, all leading to uncertainty. And uncertainty itself is a major factor in adoption decision (Marra et al., 2003). Lastly, the wide variations in household resource status of smallholder farmers imply that extension recommendations need to offer a range of options rather than the traditional optimal solution, which, even though correct from an agro-climatic perspective, are realistically only affordable by the wealthiest of farmers (Rohrbach, 1998).

A significant risk to technology adoption faced by smallholder farmers in semi-arid regions of Africa is the unreliable rainfall patterns of inter-seasonal as well as intra-seasonal distributions. One question then is how can research and extension better formulate technology options for a wide spectrum of farmers in this environment that includes indicators of associated rainfall risk and yield uncertainties to allow farmers to make more informed decisions about technology adoption? This chapter describes the application of crop simulation modeling as a tool to assist in the formulation of such options. First, it describes the application of modeling to the case of fertilizer recommendations for dry regions, by quantifying and comparing the seasonal risk of recommended and small dose fertilizer technology (see Chapter "Microdosing as a Pathway to Africa's Green Revolution: Evidence from Broad-Scale On-Farm Trials" this volume) across agro-ecological regions in Zimbabwe. It will extend this analysis to one of the most successful examples of technology adoption known in Africa, that of improved crop germplasm. Lastly, it will consider the issue of residue management central to the conservation agriculture (CA) concept currently been widely promoted in parts of Africa.

Materials and Methods

The Model

ICRISAT's applied simulation work in southern Africa uses the *A*gricultural *P*roduction *S*ystems S*im*ulator (APSIM). APSIM is a modeling environment that uses various component modules to simulate cropping systems (McCown et al., 1996; Keating et al., 2002). Modules can be biological, environmental, managerial, or economic. The modules are not directly linked with each other and can therefore be plugged in or pulled out of the modeled scenario depending on the specifications for the simulation task.

APSIM has the ability to simulate the growth of a range of crops (Table 1) in response to a variety of management practices, crop mixtures, and rotation sequences, including pastures and livestock. Importantly, this is accomplished in such a way that the soil accrues the effects of the different agricultural practices such as cropping and particular crops, fallowing, residue management, and tillage. In this way, APSIM can simulate long-term trends in soil productivity due to fertility depletion and erosion. APSIM contains modules that permit the simulation of soil organic matter rundown, nutrient leaching, soil erosion, soil structural decline, acidification, and soil phosphorus. There is however no current capability to deal with effects of salinization, insects, diseases, or biodiversity loss.

Table 1 APSIM crop, soil, and management modules

APSIM crop modules	Maize, sorghum, millet[a], wheat, sugarcane, chickpea, mung bean, soybean, barley, groundnut, canola, cotton[b], faba bean, lupin, pigeon pea[a], mucuna[a], hemp, sunflower, lucerne, annual medic, trees, weeds[a]
APSIM soil and related modules	Soil N, soil P, soil wat, SWIM[c], solutes, residue, manure[a], erosion, soil pH[d]
APSIM management modules	Manager, fertilize, irrigate, accumulate, operations, canopy

[a]Developed in association with ICRISAT and CIMMYT
[b]By arrangement with CSIRO Cotton Research, Australia
[c]By arrangement with CSIRO Land and Water, Australia
[d]Developed in association with CSIRO Land and Water

The suitability of APSIM to simulate crop productivity in smallholder farming systems in semi-arid tropical Africa has been tested over several years and in a number of regions. Building on the work of Keating et al. (1991) in Kenya, the APSIM model has been tested and used to simulate surface runoff and erosion (Okwach et al., 1999), N fertilizer response (Shamudzarira and Robertson, 2002), manure and P responses (Carberry et al., 2002), water use efficiencies (Dimes and Malherbe, 2005), legume rotational effects (Ncube et al., 2007), crop–weed interactions (Dimes et al., 2003), and extrapolation of research findings to other sites (Rose and Adiku, 2001).

Model Inputs

Long-term daily climate data for Harare (1951–2000), Masvingo (1951–1998), Beitbridge (1952–1997), and Bulawayo (1951–1999) were used to simulate maize yields across the agro-ecological regions of Zimbabwe. The cropping season (November–April) mean annual rainfall for the four sites are Harare, 780 mm, Masvingo, 580 mm, Beitbridge, 300 mm, and Bulawayo, 550 mm. Twomlow et al. (2007, these proceedings) report the main features of the smallholder farming system in Zimbabwe.

The technology options simulated are maize response to alternative N fertilizer investments and long (sc601) and short (sc401) duration cultivars. The baseline simulation for farmer practice is no N inputs (all other nutrients are assumed non-limiting and there are no pest and disease constraints). The simulated N fertilizer inputs are 1 or 3 bag(s) ammonium nitrate (AN) fertilizer (17.5 and 52 kg N/ha) at 35 days after sowing. The three bags of top-dress fertilizer is the extension recommendation that broadly applies across the agro-ecological regions of Zimbabwe.

Maize response is simulated for a shallow sand (PAWC = 60 mm, 1 m rooting depth) of low fertility (OC% = 0.6) or a deep sand (PAWC = 120 mm, 1.7 m rooting depth) of medium fertility (OC% = 1.0). In the simulations, a maize crop is planted each year of the climate record when a planting rain occurs between November 20 and January 10. Seasons were simulated independently by re-initialization of water and N (PAW = 0, mineral N = 10 kg N/ha, OC% = 1.0 or 0.6%) on 19th November each year. Plant population was 2 plants m^{-2} (approx. farmer's population in SAT regions) when comparing cultivar response and the extension recommendation of 3.7 plants m^{-2} when comparing N response. Re-setting PAW to zero assumes that pre-sowing rainfall is largely lost via soil evaporation and/or weed growth. Re-setting OC% each year ensures simulated yield outputs are not confounded by effects of soil fertility decline. All simulations assume no weed competition. For all scenarios, maize residues are removed at crop harvest.

Where value cost ratios for N investment with maize is presented, the price of maize grain is Z$7500 per ton and the price of AN fertilizer is Z$800 per bag. These prices last applied in Zimbabwe in 2001 when the N:maize price ratio was 6.3. This ratio is similar to the current ratio of 6.7 applicable in Republic of South Africa at the time of reporting (August 2007).

Results and Discussion

Regional Responses to N Top-Dress Fertilizer

Figure 1a shows simulated maize yields for Harare and the three N fertilizer treatments – no applied fertilizer, the recommended 3 bags/ha (52 kg N/ha), and a

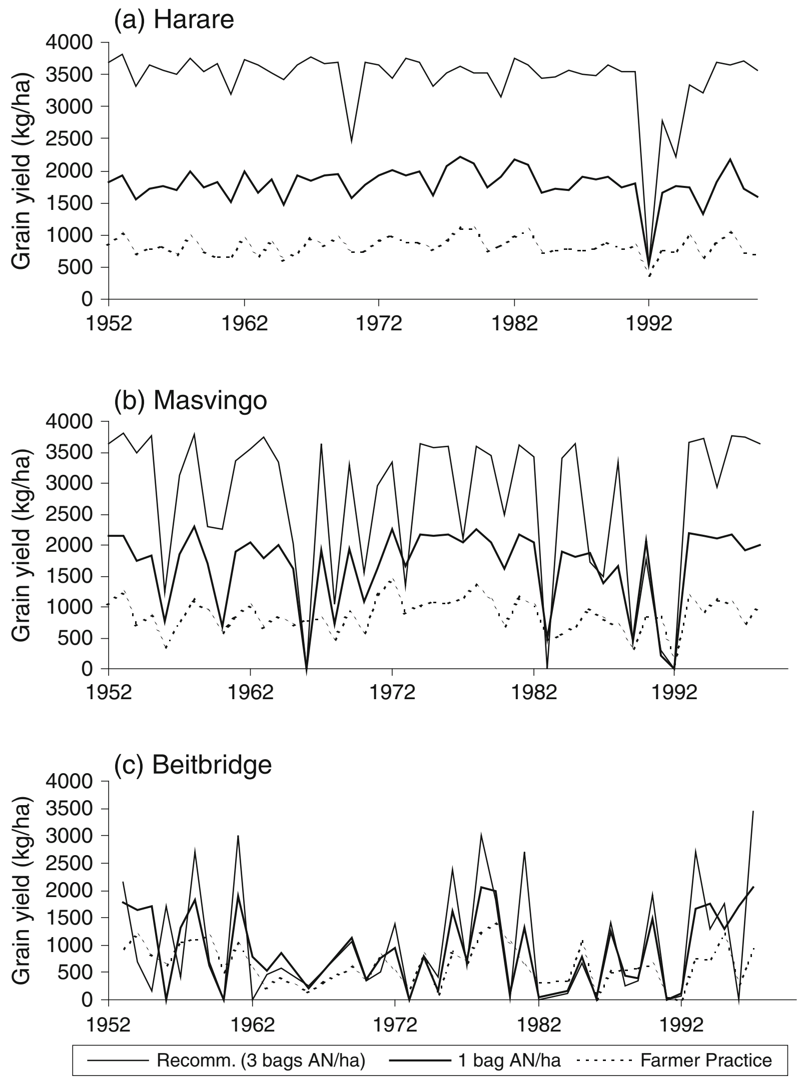

Fig. 1 Simulated maize yield (cultivar SC401) on a deep sand soil at (**a**) Harare, (**b**) Masvingo, and (**c**) Beitbridge, Zimbabwe, for climate records starting in 1952 and N inputs of 0 (farmer practice), 17 (1 bag AN/ha), and 52 kgN/ha (Recommended, 3 bags/ha)

smaller investment of 1 bag/ha (17 kg N/ha). Simulated yields are very stable at Harare, except for the 1992 season. This result reflects the reliable rainfall in this region, and as a consequence, there is a consistent and clear response to the application of N fertilizer.

In Fig. 1b, c simulated maize yields for Masvingo and Beitbridge and the three N fertilizer treatments are shown. Simulated yields are highly variable at Masvingo, reflecting the variable rainfall in this region. For the recommended treatment, there are many years with good responses to N fertilizer but also years when there is no yield advantage. At lower N inputs, the response to N is more stable and mostly above that with no N fertilizer input.

In contrast, at Beitbridge, simulated yields are mostly low and highly variable, reflecting the extremely low and variable rainfall in this region. There are a few years with good responses to N fertilizer but most years there is no yield advantage to N application.

Figure 2 shows the Z$ return in maize grain production per Z$ invested in N fertilizer for simulated crops at Masvingo for 1 bag/ha (17 kg N/ha) compared with the recommended 3 bags/ha (52 kg N/ha). Returns on fertilizer investments are often high (>Z$7/Z$ invested) and at the lower level of investment, reasonably stable across the 45 years of simulation. Returns at the higher level are much more

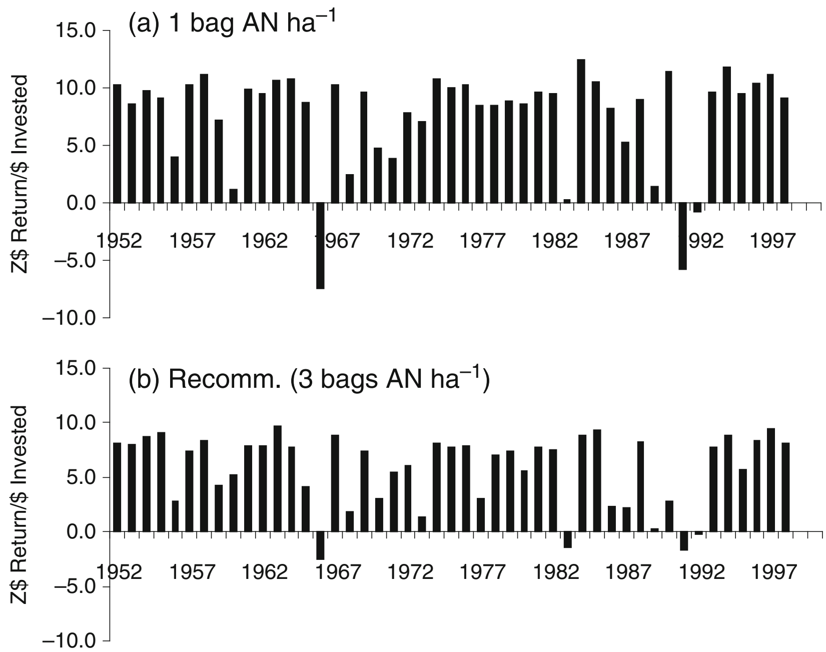

Fig. 2 Z$ return in maize grain production per Z$ invested in N fertilizer for simulated crops at Masvingo for (**a**) 1 bag AN/ha (17 kg N/ha) and (**b**) the recommended 3 bags AN/ha (52 kg N/ha)

variable with many seasons having little or no return on investment.

Figure 3 graphs use the simulated returns on investment for each year and re-plot the data as cumulative probabilities of achieving a Z$ return per Z$ invested in fertilizer for Harare, Bulawayo, Masvingo, and Beitbridge. Cumulative probability plots quantify the riskiness of different investment options. The above graphs indicate that a fertilizer investment of 1 bag/ha has only low probabilities of loss at Harare and Bulawayo, a slightly higher chance of loss at Masvingo, but very high loss probabilities at Beitbridge. A fertilizer investment of the recommended 3 bags/ha has low chance of loss at Harare,

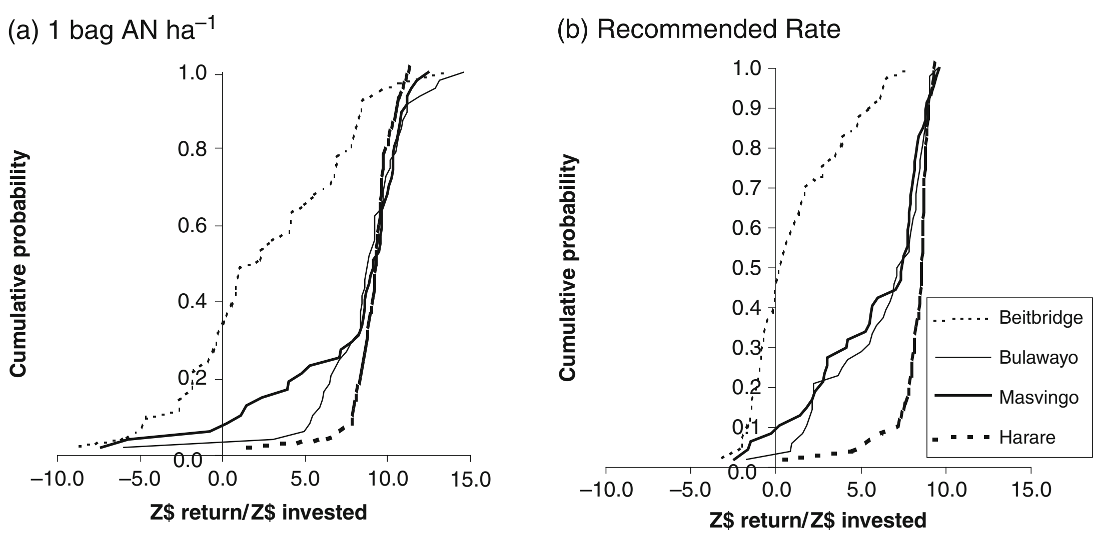

Fig. 3 Cumulative probability distributions for simulated returns on investment in fertilizer for Harare, Bulawayo, Masvingo, and Beitbridge – (**a**) 1 bag/ha (17 kg N/ha) and (**b**) recommended, 3 bags/ha (52 kg N/ha)

Table 2 The percentage of years that maize grain yield can be expected to attain various yield thresholds at Harare and Masvingo in response to N inputs

	Harare			Masvingo		
Yield (kg ha^{-1})	0N	Low N	Recomm. N	0N	Low N	Recomm. N[a]
<500	2	0	0	11	11	11
500–1000	85	2	2	51	6	0
1000–1500	13	4	0	38	4	9
1500–2000	0	79	0	0	40	6
>2000	0	15	98	0	38	74

[a]Recommended N

but is in the order of 10% of years at Bulawayo and Masvingo and 50% at Beitbridge.

The above results provide different approaches to using simulation output as a means to quantifying the climatic risk of fertilizer investments across rainfall gradients in Zimbabwe. However, they are not in a format readily understood by farmers or extension officers for that matter. Table 2 is an example of how the same data for two of the regions might be presented to smallholder farmers who are thinking about investing in top-dress fertilizer and who are restricted to 1 ha of cropland.

At Harare, a smallholder farmer who does not currently apply top-dress N and is interested in ensuring food security can learn from Table 2 that a small investment will shift the odds dramatically away from a food-insecure situation (<1000 kg) to one of food security with a higher chance of surplus grain than that of deficits. On the other hand, a farmer wanting to venture into the commercial grain market would see that one could make the necessary fertilizer investment in line with the extension recommendation with very little risk of crop failure.

At the drier Masvingo site, there are about 10% of years when drought will seriously limit crop yields irrespective of the N management (in the absence of any weed, pest, or disease constraints). However, a small investment in N will allow the farmers maize to make more efficient use of the rainfall in the majority of seasons, such that food deficits could reduce from over 60% of years to around 15%. For the more commercially orientated farmer at Masvingo, the recommended N rate should provide surplus grain for sale in about 75% of years. However, in approximately 20% of years, there will be insufficient grain for sale to re-coup the fertilizer investment, after allowing for household consumption. While some smallholder farmers in this region will have the resource status and risk aversion profile to take up this option, the majority will not.

Cultivar Responses in a Semi-arid Rainfall Environment

Simulated maize yield for long- and short-season cultivars (representing traditional and improved, respectively) with no N inputs for shallow sand at Bulawayo is shown in Fig. 4. The output clearly shows that the short-duration cultivar provides fewer seasons of complete crop failure compared to the long duration (2 vs 8). This is consistent with the expected benefits and rationale of breeding programs targeting short-duration varieties for this environment. However, the simulated long-term average grain yield for both cultivars is low (long = 664 kg/ha, short = 680 kg/ha) and the year-to-year variability high, although substantially less for the short-season cultivar (stdev = 298 vs 436 kg ha^{-1})

In Fig. 5, results in Fig. 4 are converted into an annualized difference for the cultivar responses. The effect of applying N fertilizer is also included in Fig. 5. In Fig. 5, a positive value in any year represents the yield advantage in that season for the technology indicated above the *x*-axis, and a negative value represents the yield advantage of the alternative technology indicated below the *x*-axis.

With no N applied (Fig. 5a), the yield advantage of the short-season cultivar averages 300 kg/ha and is achieved in 48% of years. In comparison, the long-season type has an average yield advantage of 250 kg/ha and is achieved in 52% of years. If a small amount of N is applied (Fig. 5b), then there is a considerable shift in favor of the short-season cultivar – average yield advantage is 600 kg/ha, and an advantage is seen in 60% of years. But in 40% of years, the

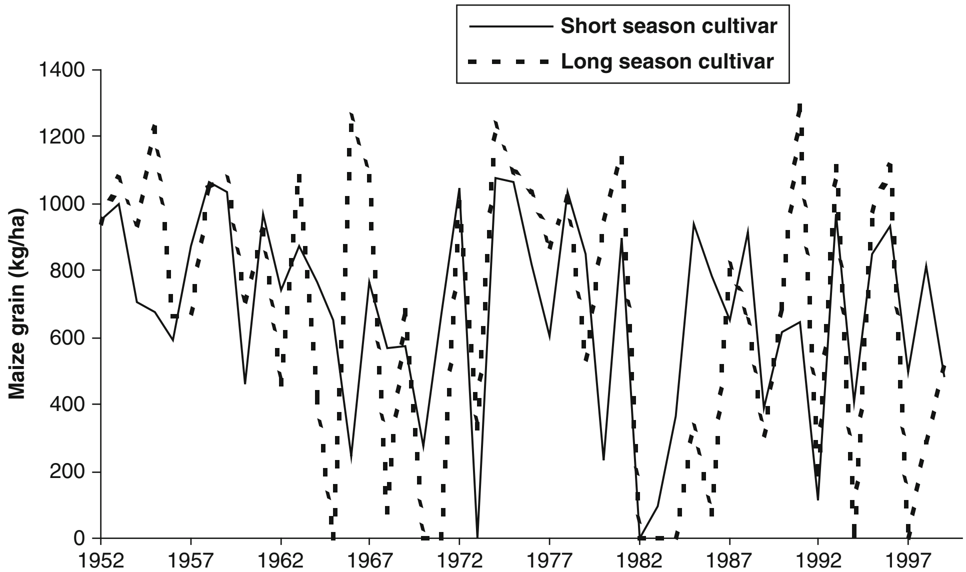

Fig. 4 Simulated maize grain yield for long- and short-season cultivars with no N inputs on shallow sand at Bulawayo for cropping seasons 1951–1998

long-season cultivar still outperforms the short-season cultivar with an average grain advantage of 390 kg/ha.

The cultivar analysis presented here shows that in these environments, rainfall distribution patterns can actually favor the long-season cultivar in a high proportion of seasons. This fact has largely been overlooked in breeding and extension programs for drier areas – which tend to concentrate on short-season varieties to avoid terminal moisture stress. The analysis also helped to highlight that water productivity increases in this environment only really come about with investment in fertility management (Figs. 4 and 5b).

Residue Management and Conservation Agriculture in Dry Areas

Conservation agriculture is promoted as a more sustainable approach to crop production with more efficient use of rainfall and protection of the soil resources. Currently, it is being widely promoted in smallholder agriculture in sub-Saharan Africa, including the semi-arid regions (Twomlow et al., 2006). One of the cornerstones of this technology is retention of crop residues as a surface mulch to reduce runoff and soil erosion. To this end, CA advocates a minimum of 30% ground cover and in Zimbabwe's maize cropping systems, it has been established that at least 2 t/ha of maize residues is required to comply with the 30% threshold. CA proponents generally acknowledge that in the mixed farming systems common in the semi-arid regions there will be competition for crop residues as a livestock feed. However, there is less recognition of the residue production potential of cropping in these environments and implications for achieving the desired ground cover threshold.

In Table 3, the stover yields associated with maize grain yields displayed in Fig. 1b, c have been analyzed to provide estimates of the percentage of years in which residue thresholds will be achieved with varying levels of N input. At Masvingo, model output suggests that 90% of years will produce sufficient stover to achieve the 2 t/ha threshold, even with no N input. With increasing N inputs, increasing amounts of residue could be fed to animals while retaining the desired mulch cover. However, only at the highest N input is sufficient excess residues produced to feed animals commensurate to the existing feeding regimes (i.e., 0N treatment, approx. 2 t/ha of crop residues) and then only in 65% of seasons. As suggested above, only the wealthiest of farmer in this environment will have the resources to pursue this level of N investment and associated climatic risk.

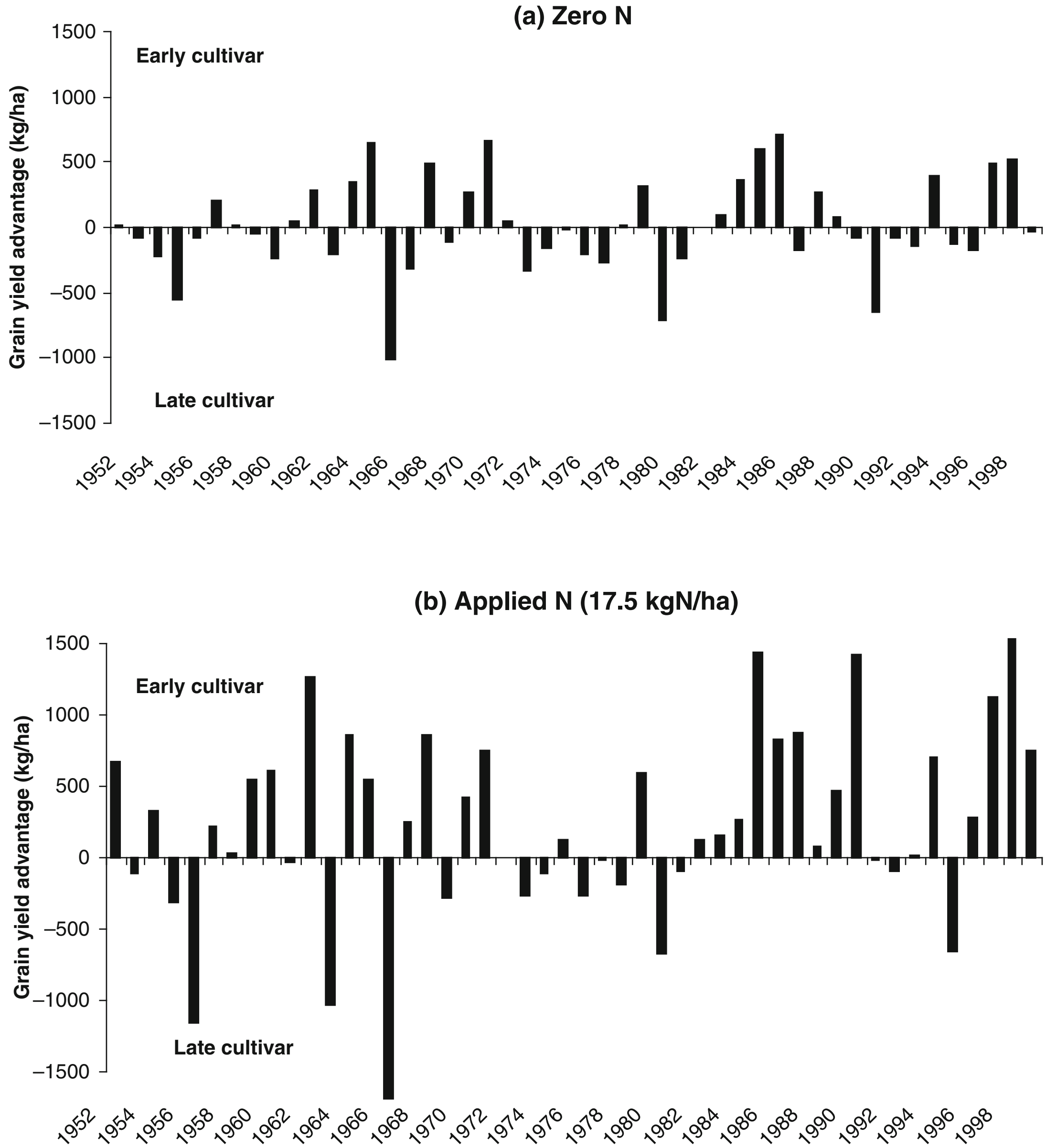

Fig. 5 Annual grain yield difference between short- and long-duration maize cultivars simulated for Bulawayo (**a**) without and (**b**) with N fertilizer applied

Table 3 The percentage of years that maize stover yield can be expected to attain various yield thresholds at Masvingo and Beitbridge in response to N inputs

	Masvingo			Beitbridge		
Stover (kg ha^{-1})	0N	Low N	Recomm. N	0N	Low N	Recomm. N[a]
<1000	2	6	8	15	17	23
1000–2000	8	2	0	60	33	25
2000–3000	90	33	2	25	48	29
3000–4000	0	58	25	0	2	23
>4000	0	0	65	0	0	0

[a]Recommended N

At Beitbridge, production of crop residues is much lower, and 75% of years do not reach the 2 t/ha threshold with 0N input. Even with N inputs, a deficit to the threshold will occur in approximately 50% of years. Of course, in this water-limited environment, it might be expected that the water conservation offered by a mulch would have a significant effect on maize yield and stover production and their responses to N inputs. This effect is not included in the simulation output used in this analysis.

Conclusions

The focus of this chapter has been crop improvement technologies for maize cropping systems under highly variable rainfall regimes. By definition resource-poor, smallholder farmers in such environments are strongly risk averse and seasonal rainfall variability will be a major risk factor in any technology adoption decision. Yet, almost no crop management recommendations given to farmers by research and extension in Africa include any estimates of the variation in technology response that can be expected due to climatic risk.

As an example, the area-specific fertilizer recommendations developed in Malawi and reported by Benson (1998) were undoubtedly a response to the Blackie statement of 1994. The new recommendations were based on over 1600 yield response trials to fertilizer inputs across all ecological cropping zones of Malawi. This research effectively resulted in the formulation of seven fertilizer recommendations to cover all areas of the country in place of the previous blanket recommendation. The new formulations are designed to take account of four farmer production objectives and two soil texture combinations. While this is a clear step in the right direction, nowhere do the new recommendations provide any information on expected yield variations due to seasonal rainfall conditions.

This chapter has hopefully demonstrated that crop simulation models provide a cost-effective pathway to assist formulation of crop management options that can take variable rainfall conditions into account. Only when research and extension are able to report both the positive and negative responses of a technology due to variable rainfall conditions will there be improved learning by both researchers and farmers. Such information is essential if risk-averse farmers are to be encouraged in their adoption of improved management technologies, especially in drier areas.

Of the 205 abstracts received for this symposium, only this chapter and one other included the word "risk" in its title. For a green revolution in sub-Saharan Africa to be realized, this suggests that there needs to be a dramatic turnaround by research and extension in its focus on climatic risk.

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