Invited Keynote Paper, 5th Australian Sorghum Conference, 30 Jan-2 Feb 2006, Gold Coast, Australia

Pathways to Prosperity: Breaking the Yield Barrier in Sorghum

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Abstract

In the next decade, we have an unprecedented opportunity and the capacity to pursue rapid production advance in sorghum in Australia. Demand for sorghum grain from intensive livestock and ethanol industries is high and is outstripping our ability to supply. The current rate of yield and production advance is shown to be inadequate to realise this development opportunity. In this paper novel approaches to breaking the yield/production barrier in sorghum are outlined. They involve simultaneously exploring management (M) and genetic (G) plant trait manipulations for the likely levels of the major limiting resource in our production environments (E) – water. More effective capture of water and its more efficient use to produce grain are common features of the useful manipulations identified. The key concept is to establish crop canopy size targets that enable some crop water use as transpiration to occur after anthesis of the crop. A specific case study detailing this concept is presented and discussed. This G*M*E approach could generate increased or more reliable yield per unit area as well as underpin expansion in cropped area. Implementation of this approach to hasten yield advance requires an integrated systems approach to crop improvement among agronomists, plant breeders, and physiologists/modellers. Use of the G*M*E modelling technology in a production capability assessment of potential sorghum cropping land is suggested as a means to inform industry planning and policy on potential to expand cropped area.

Introduction

We are faced with an unprecedented opportunity to expand the grain sorghum industry in NE Australia. Demand for sorghum grain into the foreseeable future is remarkably bullish. Growth in intensive livestock industries in NE Australia has generated high demand for feed grains. Sorghum is one of the major feed grains produced in the region. Recent analyses have shown that our capacity to meet feed grain demand is already stretched, especially in El Nino years (Hammer et al., 2003). The demand situation is exacerbated by increasing global demand for meat products as diets change in the developing world (Johnson, 2006) and by the potential use of sorghum grain as a feedstock for ethanol production as plants come on line in the region (Pfeffer, 2006).

We must produce more sorghum to take advantage of this industry development opportunity. We need to break existing yield and production barriers. This paper speculates about how. In reflecting on this, three issues are considered -

1. What is the yield/production barrier?
2. How can we break it?
3. What are the industry and policy implications?

What is the yield/production barrier?

Sorghum is the major summer grain crop grown in Australia. Over the five years to 2003-04, the average production of sorghum in Australia was 1.9 Mt, the crop occupied an average planted area of 0.72 Mha, and average yield was 2.67 t/ha (ABARE, 2006). Over this period, domestic use ranged from 1.4 to 1.6 Mt and any surplus was exported. Within Australia, sorghum production has been relatively evenly distributed between the three geographic regions of Central Queensland, Southern Queensland and Northern New South Wales.

The period since the turn of the century has seen a 'step-up' in sorghum production (Fig. 1). This has been associated with both a generally high planted area (data not shown) and higher yield per unit area (Fig. 2). However, it is not clear whether this recent increase in yield per unit area is associated with seasonal effects or represents an enhanced technology (eg. genetics, agronomy) or other effect (eg. greater proportion of more productive land used). Potgieter et al (2005) have conducted a detailed analysis of yield trends in sorghum for the period 1983-1997. They incorporated a rigorous modelling approach that allowed for removal of fallow and seasonal rainfall effects in their time series analysis. Their residual yield trend values ranged from 0 to 5% per annum depending on location, with most significant increases concentrated

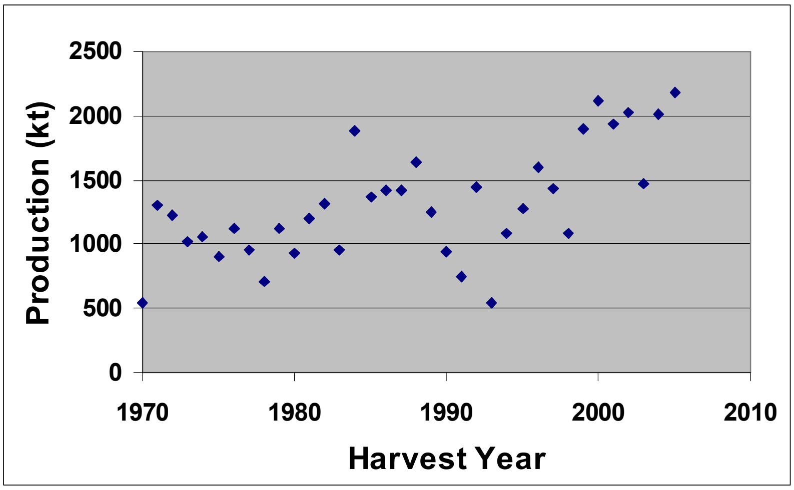

Figure 1. Total annual production of sorghum in Australia (kt) since 1970. The production occurring in each growing season (eg. 1999-2000) is plotted against the associated harvest year (eg. 2000). (Source – ABARE)

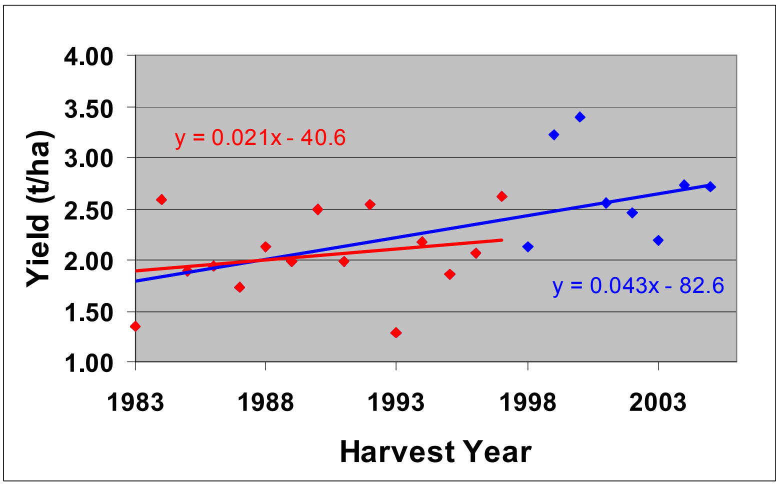

Figure 2. Average grain yield of sorghum in Australia (t/ha) from 1983 to 2005. The trend lines and associated linear regressions are for data for the whole period (blue) or for the period 1983 to 1997 (red). (Source – ABARE)

in Northern New South Wales (Fig. 3). At the aggregate scale, this was consistent with the simple linear regression on national data for the same period (Fig. 2), which gave an average yield trend of around 1% (0.021 t/ha/annum on a long-term median yield of 2.25 t/ha). When more recent data were included, the linear regression generated an average yield trend of near 2%. However, this increase was affected greatly by the two very high-yielding years of 1999 and 2000. It is likely that the real underlying yield trend remains close to that reported by Potgieter et al. (2005). Although an update of their analysis would be useful, the short-sighted federal government decision in the late 1990's to discontinue the annual census conducted by the Australian Bureau of Statistics makes rigorous time series analysis near impossible due to spatial and temporal limitations in data coverage.

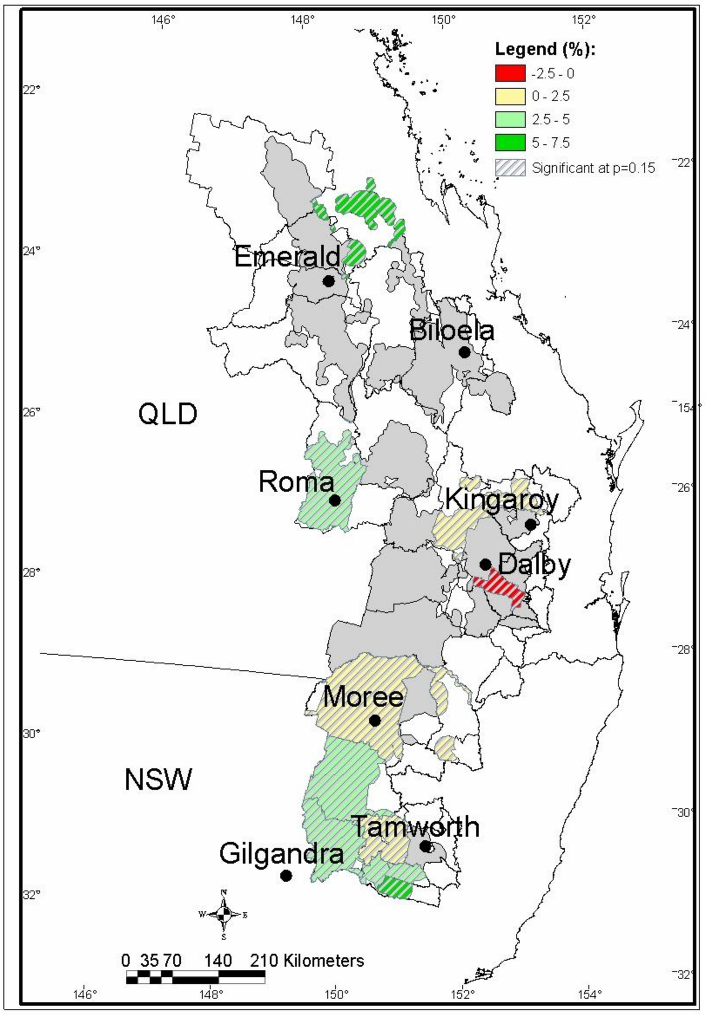

Figure 3. Percentage annual trend in sorghum yield (t/ha) over the period 1983-1997 for all sorghum-producing shires in NE Australia once the growing season rainfall effect has been removed by modelling (after Potgieter et al., 2005).

Nonetheless, it is clear that the current rate of yield and production advance in sorghum is not adequate to support the rate of increase in industry demand for feed grains (Fig. 4). Hammer et al (2003) and Yates and Coombs (2003) demonstrated clearly that growth in intensive livestock and ethanol industries could not be sustained given the current capacity to supply grain and that shortages were inevitable in drought years, as indeed occurred in 2002/03. Up to 0.5 Mt per annum of additional feed grain will be needed in the region to support industry growth. There are considerable socioeconomic and regional development advantages to be gained from continued growth of the intensive livestock and ethanol industries. Numerous options are available to tackle the feed grain supply reliability issue. These range from enhanced grain import, interstate transfer, and inter-season transfer via storage, through to producing more feed grains locally. All options may play some part. Here I focus on possible approaches to the latter in sorghum.

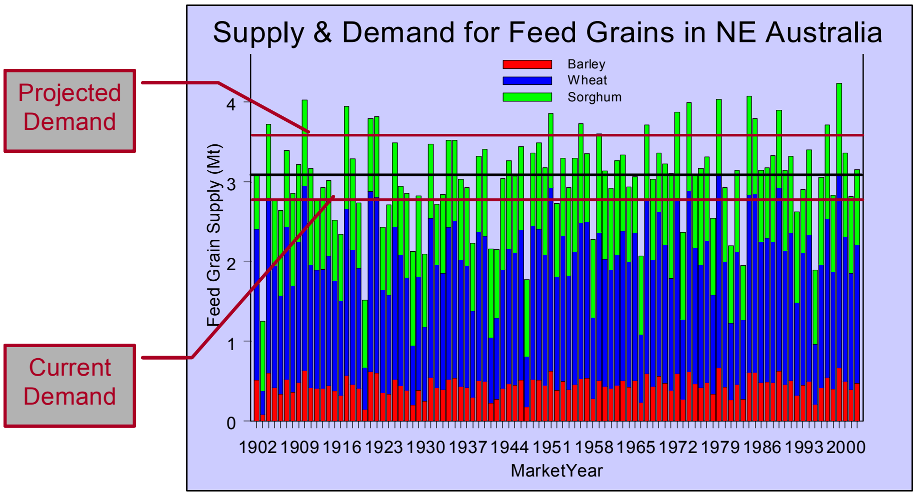

Figure 4. Analysis of the supply and demand for feed grains in NE Australia based on current production technology. The bars show simulated feed grain supply for sorghum, wheat and barley given seasonal conditions experienced for each year of the last century. The current and projected demand lines are based on analysis of industry size and projected growth (after Hammer et al., 2003).

How can we break the yield/production barrier in sorghum?

If enhanced sorghum production is to play a key role in meeting increased demand for feed grains in NE Australia, then both the area planted to sorghum and the amount and/or reliability of the amount produced per unit area must be increased. We now have a sufficient level of understanding of sorghum production environments (E), how the sorghum plant works, and how to predict how it works, to enable us to consider combinations of genotypes (G) and management (M) systems in those environments (i.e. G*M*E) to achieve the required increases in both area and yield. Further, we are in the fortunate situation that sustained investment in sorghum plant improvement over the past 20 years by the Queensland Government and industry has provided a platform for a more intensive focus on yield by virtually eliminating midge as a yield-limiting factor (Henzell and Jordan, 2006; Franzman, 2006; Jordan et al., 2006).

Water limitation dominates sorghum production environments in NE Australia, although to varying degrees (Hammer and Muchow, 1991; Chapman et al., 2000). Consequently, the focus needs to be on optimising grain yield outcomes for target amounts of available water. The key principle involved in this approach involves maximising the amount of water captured by the plant as transpiration (i.e. productive water use), while optimising its distribution pre- and post-anthesis. Appropriate plant trait and management system combinations for specific situations can be designed using this principle. Hence, the G*M*E concept is one of simultaneous manipulation of G and M to achieve optimal specific adaptation for a given E. This can involve use of known traits and management concepts, but should not be restricted to this domain as novel approaches to G and M may be required.

The general principle is best explained via a specific example. Growth and yield of a sorghum crop planted at Roma in December on a vertosol soil that was 80cm deep, held a maximum of 120mm plant available water, and had 100mm available in the profile at the time of sowing, was simulated using the APSIM crop modelling platform (Keating et al., 2003). The simulated crop was planted at 50,000 plants/ha in 1m rows using a medium-late maturing hybrid. The simulation was conducted with these same conditions using weather data for each of the past 115 years. The average (range) in simulated yield for the 115 years was 2.9 (0 – 7.3) t/ha, which was associated with 7.0 (2.3 – 13.5) t/ha of total biomass production and 274 (100 – 600) mm of in-crop rain. Given that, on average, 83mm of the water in the soil profile at sowing was used during the crop cycle, there was an average total water use of 357 mm. While the greatest part of this total (162mm or 46%) could be attributed to transpiration (T) (Fig. 5), more than half was consumed by non-productive (i.e. soil evaporation, drainage, and runoff) components of the water balance. Soil evaporation (135mm or 38%) was equivalent to about half of in-crop rainfall, reinforcing the importance of this process in losses to the system. Similarly, the change in stored soil water was equivalent to about half of the total transpiration, reinforcing the value of stored water to production. The average crop had a leaf area index (LAI) of 2.0 (m^2 green leaf/m^2 ground area) at anthesis, a harvest index (HI) of 0.4 (g grain biomass/g total biomass), and a transpiration efficiency (TE) of 4.36 g/ m^2/mm, which represents the amount of total biomass produced per mm of water transpired.

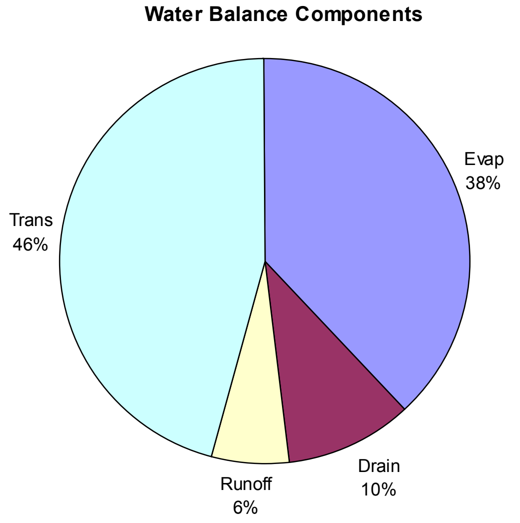

Figure 5. The average proportion of total available water (rainfall + soil water storage) associated with each component of the crop system water balance for a 100-year simulation of sorghum at Roma (see text for details).

The importance of the amount of water captured as T and its distribution pre- and post-anthesis can be simply explained by considering the identities -

Total Biomass = T*TE, and

Yield = HI*Total Biomass,

where the quantities T, TE and HI are as defined above.

Total biomass is directly related to the amount of water captured as T. This is the dominant factor affecting variation in biomass production from year-to-year in the simulation. While TE also varies, depending on the degree of atmospheric dryness (Tanner and Sinclair, 1983), the magnitude of the effect in this case is considerably less (data not shown). For the specific location and given time of year used in this example, the average TE value (4.36 g/ m^2/mm) is used subsequently to simplify calculations for the purpose of illustration.

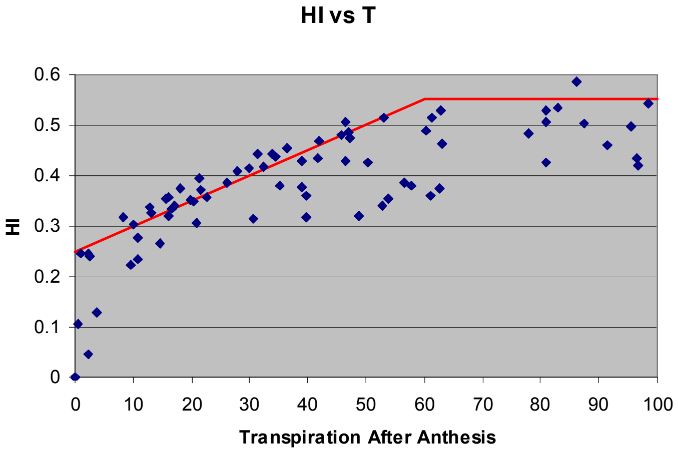

Figure 6. The association of harvest index (HI) with the amount of transpiration after anthesis for a 100-year simulation of sorghum at Roma (see text for details). The line is drawn to indicate an approximate upper bound.

HI is related to the amount of water captured as T after anthesis (Fig. 6). This association is generated by the direct effect of post-anthesis T on grain growth. If water supply is exhausted prior to anthesis and post-anthesis T is near zero, then grain growth is totally dependent on retranslocation of assimilate fixed prior to anthesis. In this situation, up to 25% of the total biomass can become grain, giving a HI of 0.25 (Fig. 6). As post-anthesis T increases, the contribution to total biomass from the additional associated growth is all allocated to grain mass, so HI is increased. For the specific case presented, this effect is saturated once post-anthesis T reaches about 60mm and HI reaches a maximum of about 0.55 (Hammer and Muchow, 1994; Hammer and Broad, 2003).

It is possible to use these simple associations to consider the consequences on grain yield of shifting T from pre- to post-anthesis. For example, given a total T of 150mm, which is slightly below the average value found in the 115-year simulation and generates total biomass of 6375 kg/ha (assuming average TE), if 60mm of this total T is shifted from pre- to post-anthesis then grain yield is more than doubled (Table 1). As an increasing amount of the 150mm is shifted to post-anthesis, the HI is increased via the association shown in Fig. 6. Hence, as total biomass remains unchanged, the result is that yield is increased as a greater proportion of the total becomes grain.

But how can T be shifted from pre- to post-anthesis to achieve this outcome? Leaf canopy development has a major effect on the rate of water use by the sorghum crop. For average growing season weather conditions, the crop canopy would need to reach a high LAI and so have near full ground cover and be intercepting all incident radiation by anthesis, if it was to use a total T of 150mm by anthesis (Table 1). For circumstances generating lower LAI and only fractional ground cover by anthesis, less of the total T is used by anthesis. For a crop that achieves a LAI of only about 2 by anthesis, radiation interception is reduced to 60%, and 60mm of the total T remains available for use post-anthesis (Table 1). This low target LAI scenario generates the highest yield for this set of circumstances.

Table 1. Total biomass (TBIO), harvest index (HI), and grain yield (YIELD) associated with a total crop transpiration (T) of 150mm that is distributed variously pre- and post- anthesis (T<A, T>A). The calculated levels of radiation interception and leaf area index at anthesis (RINT at A, LAI at A) required to achieve this distribution of total T are also given.

Total T (mm)	T < A (mm)	T > A (mm)	TBIO (kg/ha)	HI	YIELD (kg/ha)	RINT at A	LAI at A
150	150	0	6375	0.25	1594	0.95	6.66
150	130	20	6375	0.35	2231	0.88	4.79
150	110	40	6375	0.45	2869	0.75	3.06
150	90	60	6375	0.55	3506	0.61	2.10

The optimal target LAI will vary with the level of total T, which is largely dependent on the amount of in-crop rainfall. From examination of associations of water balance components with in-crop rainfall using the simulation data it is possible to determine the average in-crop rainfall required to achieve different levels of T (Table 2). For example, to realise 150 mm total T, 200 mm of in-crop rainfall is required in addition to the average 80 mm used from the soil water store. The calculation assumes that: an average amount of soil evaporation (130 mm) occurs unless there is a lesser amount of in-crop rain; there is no runoff or drainage if in-crop rain is below 200 mm; runoff and drainage is increased by 25 and 50 mm, respectively, for every 100 mm of in-crop rain above 200mm. These relationships were based on examination of the time series data from the 115-year simulation study (data not shown). They describe the main trends in the data and can be used to simplify calculations for the purpose of illustration.

Table 2. In-crop rainfall (Rain) required to achieve various levels of total crop transpiration (T) given 80mm of stored soil water (SW Store) at sowing and estimates of average soil evaporation (Evap), runoff (Runoff) and deep drainage (Drain).

Total T (mm)	Evap (mm)	Runoff (mm)	Drain (mm)	SW Store (mm)	Rain (mm)
80	100	0	0	80	100
150	130	0	0	80	200
187	130	38	75	80	350
225	130	75	150	80	500

Using this simple framework it is possible to examine the yield level that would be attained with various target LAIs for a range of in-crop rainfall amounts (Fig. 7). At low levels of in-crop rainfall (< 175mm) a very low target LAI is required to shift T to post-anthesis and generate yield ranging from 1.5 – 2.5 t/ha. Higher target LAI systems have low (or zero) yield in such circumstances because insufficient water is left for post-anthesis T. The higher target LAI systems are advantageous at higher levels of in-crop rainfall as they can take advantage of the associated higher levels of total T and produce yield levels up to 4.5 t/ha (Table 2, Fig. 7). The low target LAI system will not produce more than 2.5 t/ha in such circumstances.

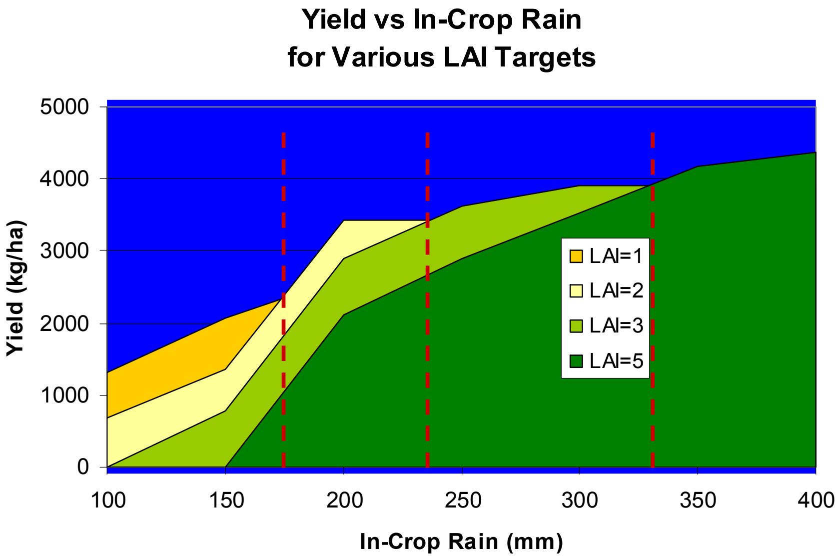

Figure 7. Grain yield versus in-crop rainfall for a range of LAI targets for a simulated sorghum crop at Roma (see text for details). The vertical dashed lines identify rainfall levels at which yield for each LAI target is at its maximum and a higher LAI target is required to achieve a greater yield.

There are various plant trait (G) and management (M) system attributes that can be modified to achieve the target LAI required for specific levels of in-crop rainfall (i.e. G*M*E). The relevant attributes are those integral to the control of canopy development. They include maturity, tillering, density, row configuration, and rates of leaf appearance and expansion. For example, sorghum leaf size data of Kim et al. (2006) indicates that a target LAI of 1 at anthesis might be achieved by growing 3 medium maturing (i.e. 16.5-leaf) uniculm plants per m^2 in 1m rows or reducing density to 2 plants per m^2 if the plants each produce 1 fertile tiller. Skip row planting systems can also be employed as they modify the degree of ground cover associated with specific levels of LAI due to their effect on canopy architecture. For example, double skip row systems (2 in 4 rows planted) with 9 medium maturing uniculm plants per m^2 in the planted rows, have a cover equivalent to a target LAI of 1 in standard 1m row configurations because half of the ground area is not covered by the crop canopy. Genetic effects associated with the stay green trait may also operate in this manner as they have been associated with aspects of leaf appearance and growth and tillering (Borrell et al., 2006; van Oosterom et al., 2006).

There is some experimental evidence to support the concept and calculations for a low target LAI system. Broad and Hammer (2004) grew sorghum in twin 1m rows spaced 6m apart under a rain-out shelter at Hermitage Research Station, Warwick in the 2003-03 growing season. The soil was irrigated to capacity (approx. 150mm plant available water) prior to planting and then all rain was excluded. Treatments (density and maturity) did not differ significantly in canopy development due to compensatory tillering. The crops reached a LAI at anthesis of about 1 and produced about 2 t/ha of grain. The root systems extended beyond 2m out from the plant row.

What if it was possible to improve capture of water by roots and improve transpiration efficiency? The former may be possible by modifying root distribution to enhance effectiveness of water extraction at depth as noted for drought-adapted wheat by Manschadi et al (2005). The latter may be possible by limiting maximum transpiration rate of the plant through restricted hydraulic conductance or hormonal regulation (Sinclair et al., 2005) or from associations with effects of height regulating genes (George-Jaeggli et al., 2006). When only 10mm additional water capture and 10% increase in transpiration efficiency are incorporated into the yield calculation used to derive the standard outcome shown in Fig. 7, there is a major shift in outcome (Fig. 8). Much higher yield levels result for low levels of in-crop rain.

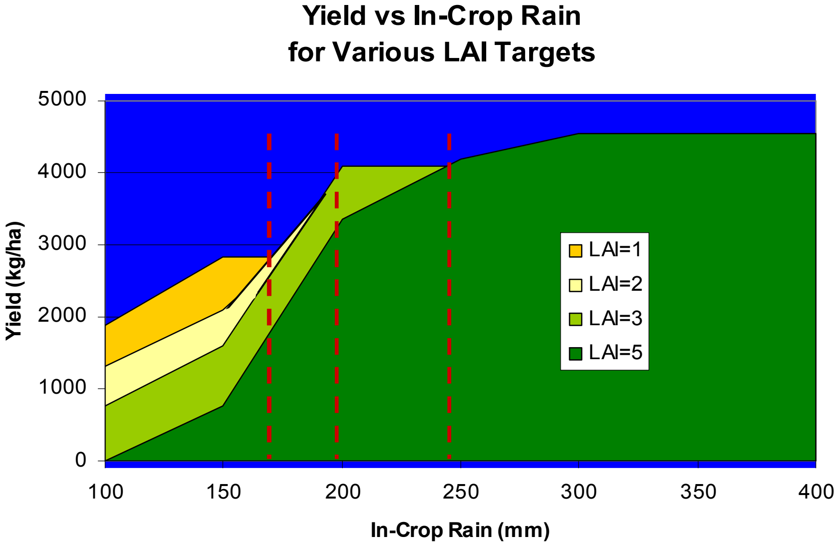

Figure 8. Grain yield versus in-crop rainfall for a range of LAI targets for a simulated sorghum crop at Roma (see text for details) that is able to extract 10mm more soil water and use it 10% more efficiently than the standard (as shown in Fig. 7). The vertical dashed lines identify rainfall levels at which yield for each LAI target is at its maximum and a higher LAI target is required to achieve a greater yield.

With these genetic modifications the very low target LAI system can now generate yield ranging from 2.0 – 3.0 t/ha. Also, much less in-crop rain is required before shifting to higher target LAI systems. A yield level of 4 t/ha can now be achieved with only 200mm in-crop rain.

Hence, small genetic modifications can generate large consequences on yield when combined with appropriate management systems for specific target environments. This is the essence of the G*M*E concept. Similar analyses could be undertaken for high yield situations, where capture of radiation becomes the limiting factor. In such situations, modifications to generate rapid canopy development would be desirable. This could include genetic manipulations to favour late maturity and increased partitioning to leaf, combined with management manipulations to favour high density and narrow row spacing. Genetic modification of radiation use efficiency, via possible associations with height (George-Jaeggli et al, 2004), would also be advantageous in these circumstances.

What are the industry and policy implications?

Implementing the G*M*E concept to improve yield per unit area involves shifting away from a production strategy of general adaptation to one of specific adaptation. Combinations of G and M suited to specific target environments will differ and be mutually exclusive. Combinations designed for marginal moisture situations (low LAI target) generate reliable but low yields, even if the season is favourable. Combinations designed for high moisture situations (high LAI target) generate higher yields but have a tangible risk of failure if the season is unfavourable. It is not possible to convert fully between options during the season as the dynamic of the water use patterns is initiated very early in the crop cycle. There is already some adoption of the specific adaptation approach via manipulation of management systems. Low density, wide row systems have become accepted in marginal conditions and higher density, narrow row systems in more favoured conditions (Collins, 2006; Butler, 2006). There is also some use of seasonal climate forecasting to aid decisions on the most suited combination (Nelson et al., 2002; Cox et al., 2004).

The major gap in implementing the G*M*E concept is in the integration of G and M aspects in crop improvement programs. Physiological understanding and modelling can play a key role in supporting such integration. They provide a means to project likely consequences of G and M combinations in specific environments and, hence, assess their potential. For example, as noted earlier, the low LAI target system suited to marginal moisture situations could be achieved by simultaneous regulation of tillering (G) and density (M). More generally, physiology and modelling provide a means to dissect the process regulation of complex traits in a way that could add significant value to use of molecular approaches in plant breeding (Hammer et al., 2005). Current research effort is targeting such an integrated systems approach to crop improvement (Jordan et al., 2006) but this will require long-term investment in relevant partnerships and expertise. Ultimately, simultaneous development of superior G and M modifications for specific E would arise from such an approach.

The G*M*E concept provides a significant opportunity to assess land capability for producing sorghum and identify opportunities to expand production area. Analysis of production potential using advanced modelling tools is now possible for all existing and potential production areas. Such tools were not available when previous comprehensive, but largely qualitative, assessments (e.g. Weston et al., 1981) were undertaken. A quarter of a century on, it is now timely to re-visit the assessment of land capability for grain production.

Planning and co-ordination at industry scale and associated policy decisions could be influenced by a production capability assessment. For example, using the low LAI target system it may be physically possible to reliably produce enough sorghum in a new area to support local growth in the intensive livestock industry or development of an ethanol plant. But there are trade-offs in the economic viability of such regional development that are not well catered for by market forces. For example, reliable long-term supply from growers would likely involve low risk, low yield, production systems. The enhanced reliability should draw a price premium for production opportunities forgone in good seasons. Given appropriate co-ordination, it should be possible to reach an equitable and profitable arrangement for all players so industry development can advance. But it is often not in the individual interests of sectors of the supply chain to take such a broader view. There are likely to be opportunities for novel policy instruments and incentives to support industry planning and co-ordination so that potential national development opportunities are realised.

Acknowledgements

I thank Greg McLean for support in conducting and analysing the sorghum simulations.

References

ABARE (2006) Australian Crop Report 137, 14 Feb 2006. www.abareconomics.com

Borrell, A.K., Jordan, D.R., Mullet, J.E., Klein, P.E., Klein, R.R., and Harris, K. (2006) Staying green is better than going brown: A leaf's perspective on a dry world. Invited paper, 5th Australian Sorghum Conference, 30 Jan-2 Feb 2006, Gold Coast, Australia (these proceedings)

Broad, I. and Hammer, G.L. (2004) Soil exploration by sorghum in wide row cropping systems. Contributed Paper in *New directions for a diverse planet*, Proceedings of the 4th International Crop Science Congress, 26 Sep – 1 Oct 2004, Brisbane, Australia. Published on CDROM. Web site www.cropscience.org.au

Butler, G. (2006) Optimising the management of grain sorghum in northern New South Wales. Invited paper, 5th Australian Sorghum Conference, 30 Jan-2 Feb 2006, Gold Coast, Australia (these proceedings)

Chapman, S.C., Hammer, G.L., Butler, D., and Cooper, M. (2000). Genotype by environment interactions affecting grain sorghum. III. Temporal sequences and spatial patterns in the target population of environments. *Australian Journal of Agricultural Research,* **50**: 223-234.

Collins, R. (2006) Optimising the management of grain sorghum in central Queensland. Invited paper, 5th Australian Sorghum Conference, 30 Jan-2 Feb 2006, Gold Coast, Australia (these proceedings)

Cox, H., Hammer, G., McLean, G. and King, C. (2004) Delivering risk information on crop management decisions to agricultural advisors throughout Australia – WhopperCropper discussion support software. Contributed Paper in *New directions for a diverse planet*, Proceedings of the 4th International Crop Science Congress, 26 Sep – 1 Oct 2004, Brisbane, Australia. Published on CDROM. Web site www.cropscience.org.au

Franzman, B.A. (2006) Impact of sorghum midge resistance in Australia. Invited paper, 5th Australian Sorghum Conference, 30 Jan-2 Feb 2006, Gold Coast, Australia (these proceedings)

George-Jaeggli, B., Broad, I., Hammer, G.L. and Jordan, D (2004) Is increased radiation use efficiency in sorghum related to increased height? Contributed Paper in *New directions for a diverse* *planet*, Proceedings of the 4th International Crop Science Congress, 26 Sep – 1 Oct 2004, Brisbane, Australia. Published on CDROM. Web site www.cropscience.org.au

George-Jaeggli, B., Hammer, G., van Oosterom, E., and Jordan, D. (2006) Tall sorghum plants use water more efficiently than short ones. Invited paper, 5th Australian Sorghum Conference, 30 Jan-2 Feb 2006, Gold Coast, Australia (these proceedings)

Hammer, G.L. and Broad, I.J. (2003). Genotype and environment effects on dynamics of harvest index during grain filling in sorghum. *Agronomy Journal*, **95**: 199-206.

Hammer, G.L. and Muchow, R.C. (1991). Quantifying climatic risk to sorghum in Australia's semiarid tropics and subtropics: Model development and simulation, in R.C. Muchow and J.A. Bellamy (eds.), *Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics*. CAB International. pp. 205-232.

Hammer, G.L. and Muchow, R.C. (1994). Assessing climatic risk to sorghum production in water-limited subtropical environments. I. Development and testing of a simulation model. *Field Crops Research*, **36**:221-234.

Hammer, G.L., Chapman, S., van Oosterom, E., and Podlich, D.W. (2005) Trait physiology and crop modeling as a framework to link phenotypic complexity to underlying genetic systems. *Australian Journal of Agricultural Research*, **56**: 947-960.

Hammer, G.L., Potgieter, A. and Strahan, R. (2003). The reliability of supply of feed grains in the northern region. Proceedings of the Fifth Australian Maize Conference, Toowoomba, Feb 2003. p.120-6.

Henzell, R.G. and Jordan, D.R. (2006) History of grain sorghum breeding in Australia, including the development of resistances to midge, drought and ergot. Invited paper, 5th Australian Sorghum Conference, 30 Jan-2 Feb 2006, Gold Coast, Australia (these proceedings)

Johnson, R. (2006) Global trends in feed grain demand and supply and implications for Australia. Invited paper, 5th Australian Sorghum Conference, 30 Jan-2 Feb 2006, Gold Coast, Australia (these proceedings)

Jordan, D.R., Hammer, G.L., and Henzell, R.G. (2006) Breeding for yield in the DPI&F breeding program. Invited paper, 5th Australian Sorghum Conference, 30 Jan-2 Feb 2006, Gold Coast, Australia (these proceedings)

Keating, B.A., et al., (2003). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy*, **18**: 267-288.

Kim, H.K., van Oosterom, E., Luquet, D., Dingkuhn, M., and Hammer, G.L. (2006) Physiology and genetics of tillering. Poster paper, 5th Australian Sorghum Conference, 30 Jan-2 Feb 2006, Gold Coast, Australia (these proceedings)

Manschadi, A.M., Christopher, J.T., and Hammer, G.L. (2005). Root growth and soil water extraction patterns of wheat genotypes differing in drought tolerance. Paper presented at Interdrought II, The 2nd International Conference on Integrated Approaches to Sustain and Improve Plant Production Under Drought Stress. 24-28 Sept 2005, University of Rome, Rome, Italy.

Nelson, R.A., Holzworth, D.P., Hammer, G.L. and Hayman, P.T. (2002). Infusing the use of seasonal climate forecasting into crop management practice in North East Australia using discussion support software. *Agricultural Systems,* **74**:393-414.

Pfeffer, L. (2006) Benefits of ethanol to the sorghum industry. Invited paper, 5th Australian Sorghum Conference, 30 Jan-2 Feb 2006, Gold Coast, Australia (these proceedings)

Potgieter, A.B., Hammer, G.L., Doherty, A. and de Voil, P. (2005). A simple regional-scale model for forecasting sorghum yield across North-Eastern Australia. *Agricultural and Forest Meteorology*, **132**: 143–153.

Sinclair, T.R., Hammer, G.L., and van Oosterom, E.J. (2005) Potential yield and water-use efficiency benefits in sorghum from limited maximum transpiration rate. *Functional Plant Biology*, **32**: 945-952.

Tanner, C.B. and Sinclair, T.R. (1983). Efficient water use in crop production: Research or re-search? In, H.M. Taylor, W.R. Jordan and T.R. Sinclair (eds.), *Limitations to Efficient Water Use in Crop Production.* American Society of Agronomy, Madison, WI. pp. 1-27.

van Oosterom, E.J., Hammer, G.L., Borrell, A.K. and Broad, I.J. (2006). What determines expression of stay-green under post-anthesis drought stress? Invited paper, 5th Australian Sorghum Conference, 30 Jan-2 Feb 2006, Gold Coast, Australia (these proceedings)

Weston, E.J., Harbison, J., Leslie, J.K., Rosenthal, K.M., and Mayer, R.J. (1981) Assessment of the agricultural and pastoral potential of Queensland. Agriculture Branch Technical Report No. 27, Queensland Department of Primary Industries, Brisbane. pp. 195.

Yates, W.J. and Coombs, R. (2003). Review Options to Reduce Feedstuff Variability in Australia. Volume 1: Main Report. Report to Meat and Livestock Australia Ltd., Sydney, NSW.