Identifying agricultural practices to sustain bamboo production in Queensland, Australia

Grant X. Zhu, Steve Ockerby, Daniel T. White and David J. Midmore[1]

Abstract

Bamboo, as a relatively new plantation crop in Australia, requires an integrated agricultural strategy as a benchmark against which improvements to optimise productivity and maximise growers' gross margin can be assessed. An important aspect of bamboo production is how to balance the productivity and returns from edible shoots and/or culms for timber. A 6-year trial was set up on an existing clumping bamboo (*Bambusa oldhamii*) grove at Eumundi, Queensland, Australia, from 2001 to 2006. Using conventional best management as a control (T1—fertilised, irrigated, early-season selection of shoots for timber culms, and designed wide clump space), five other treatment variations (T2—no irrigation during dry season, T3—late-season selection, T4—narrow spacing, T5—late-season selection, and harvesting excess shoots only as early thinning, and T6—non-irrigation, non-fertilisation, early-season selection) were imposed. Shoots and culms in each treatment were seasonally harvested during 2003–05, and the total production, i.e. fresh weight (FW) for shoots and dry weight (DW) and volume for culms, were summed for each treatment. Water-use efficiency for dry culms at c. 1.0 g/kg (total applied water plus precipitation) was not dissimilar to other species. There was a trade-off between shoot and culm production when the harvest of shoots as a vegetable was excessive. To compare bamboo productivity between treatments, a productivity index (PI) was calculated to convert the value of culm DW to relative market value of edible shoot FW using a range of ratios from 0.0–1.0 such that the value of 1 kg of culm was adjusted as a ratio of the value of 1 kg of edible shoot. We concluded that T3 was the best strategy for producing shoots only, T5 was the best for culms only, and T2 was the best for dual production of shoots and culms because it increased average relative water-use efficiency by 28%. However, the case study indicated that T3 was a financially sustainable management for growers in Australia regardless of the fluctuation in shoot and culm market prices. Additionally, a leaf chlorophyll meter proved to be reliable in estimating bamboo leaf nitrogen concentration as a guide to nitrogen fertiliser decisions.

Introduction

The first broadacre commercial bamboo farm in Australia was established in 1989 and a handbook for bamboo selection, establishment and utilisation was published 10 years later (Dart 1999). Research by Kleinhenz et al. (2003) at the same location showed that growth and yield of the running bamboo *Phyllostachys pubescens* responded strongly to increased water supply and marginally to increasing rates of fertilisation. The study showed that concentration of leaf nitrogen (N) was an early and better indicator of yield response to fertiliser than was soil N. Kleinhenz and Midmore (2002) showed that bamboo leaf N level was more responsive to N fertiliser application when the leaf N concentration was below 3%.

Frequent sampling of bamboo leaves and analysis of leaf N with wet chemistry is laborious and costly. Alternatively, soil plant analysis development (SPAD) is widely used for measuring plant total chlorophyll (TCHL) concentration, and SPAD readings have positive and linear correlations with TCHL in several crops and weeds (Turner and Jund 1991; Monje and Bugbee 1992) and are closely related to plant leaf N

1 Centre for Plant and Water Science, Central Queensland University, Rockhampton, Queensland 4702, Australia

concentration in temperate grasses (Gáborccaroník 2003), rice (Peng et al.1996) and wheat (Debaeke et al. 2006). SPAD may be useful for measuring bamboo leaf N concentration for fertiliser decision-making.

To promote bamboo shoot and culm (pole) production, irrigation is required when rainfall is insufficient (Lin 1996). In a clay soil with well-watered condition, Kleinhenz and Midmore (2002) suggested that approximately 3,300 mm annual rainfall equivalent water can be transpired by bamboo in Queensland, Australia, but for high shoot yield, it is important to ensure that 2,000 mm water is provided 1–2 months before, and during, the shoot season.

In addition to N, potassium (K) is crucial for bamboo leaf and stem development (Kleinhenz and Midmore 2002), particularly for timber production. Kleinhenz and Midmore (2001) summarised existing reports on bamboo agronomy and silviculture and determined that average application of N, phosphorus (P), and K were 318, 149 and 126 kg/ha/year, respectively, and higher amounts (523, 226 and 228 kg/ha/year) were applied for shoot-only production than for shoot and timber (315, 97 and 142 kg/ha/year) or timber-only (225, 135 and 89 kg/ha/year).

Clump population and culm number per clump also affect harvested quantities of shoots or timber or both. Kleinhenz and Midmore (2002) specified that for *Bambusa oldhamii* the optimal culm population was c. 3,600/ha for shoots and timber, based on a strategy of retaining three 1-year-old, three 2-year-old and three 3-year-old culms (denoted as a 3-3-3 standing culm density) in a stand of 400 clumps/ha.

For optimal and sustainable shoot and timber production, it is imperative to establish a benchmark for agricultural management that includes irrigation, fertilisation and thinning regimes. Based on that benchmark, new management practices can be identified to facilitate the production goals of growers (such as shoots only or timber only or both) while sustaining productivity. Water use and nutrient (particularly nitrogen) use efficiencies are major concerns of growers intent on increasing their gross margin with either similar or increased production, and we aimed to quantify those variables.

Materials and methods

Site selection and experimental design

A bamboo (*Bambusa oldhamii*) plantation established in 1991 at Belli Park, Eumundi (26°28'S, 152°56'E, 120 km north of Brisbane) in Queensland, Australia, was selected for the experiment. Clumps were growing in rows 5 m apart and with 5 m between clumps within the row (400 clumps/ha). The experiment was established on 11 September 2001 by overlaying the experimental design within the plantation, thinning the existing clumps to reduce culm numbers to the desired value and according to treatment, separate versus close spacing between culms within a clump, and installing facilities for irrigation and related soil-moisture measurement. A randomised complete block design with four replicates was used for the experiment with treatments as detailed in Table 1. Plot size comprised three clumps, the middle of which was reserved for most data collections.

The average annual rainfall at the site for 1995–2005 was about 1,466 mm, of which about 68% (1,045 mm) occurred just before and within the shoot and wet season (November–April) (see Figure 1 for 2002–05).

Table 1. Treatment details of the experimental design at Belli Park, Eumundi, Queensland, Australia

Treatment		Treatment details				
Code	Name	Irrigation	Fertiliser	Selection of shoot for timber	Designed clump space	Edible shoots harvested
T1	Control	Yes	Yes	Early-season	Wide	Yes
T2	Dry-season[a] stress	Not during dry season	Yes	Early-season	Wide	Yes
T3	Late-season selection	Yes	Yes	Late-season	Wide	Yes
T4	Narrow Spacing	Yes	Yes	Early-season	Narrow	Yes
T5	Rhizome stress	Yes	Yes	Late-season	Wide	No[b]
T6	Unmanaged clump	No	No	Early-season	Wide	Yes

a Dry season for purposes of this treatment was defined as the beginning of May to the end of August

b In excess of the five required per year for the treatment were removed just before next shoot season to keep the wide spacing

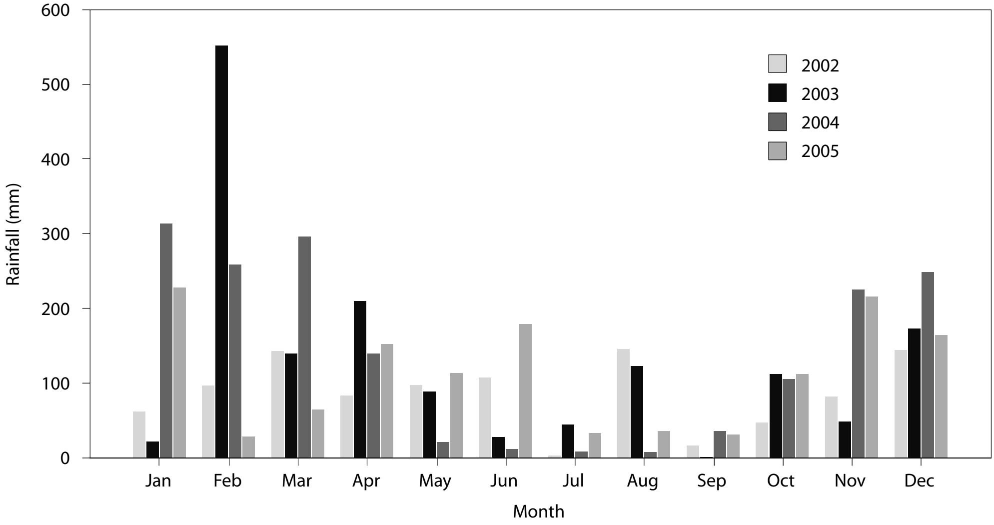

Figure 1. Monthly rainfall for 2002–05 at Eumundi, Queensland, Australia

According to Kleinhenz et al. (2003), the soil at the site is an acidic clay (pH < 6.0) with low availability of N, P, K and organic carbon (C), and high levels of manganese and aluminium.

Details of the treatments

The trial used a 5-5 standing culm density, such that each year, five 1-year-old and five 2-year-old culms were retained in the clump, and 5 new shoots were grown each year to develop into culms. The five 2-year-old culms were harvested before the next shoot season (at an average age of 2.5–2.8 years).

Irrigation was applied to only the clump area (3.5 m maximum diameter) to replace pan evaporation validated by use of tensiometers (three/plot) installed in the control treatment (T1) and unmanaged clumps (T6) at depths of 15, 30 and 50 cm to monitor soil moisture. Before irrigation began, soil samples were taken at 0–5 cm and 12.5–17.5 cm to determine soil gravimetric water content (%), and tensiometer readings at the corresponding sites were recorded. Linear regression analysis confirmed that the mean soil moisture content at 0–17.5 cm was closely related to the tensiometer readings averaged at 15, 30 and 50 cm (Figure 2a). Tensiometer readings at 50 cm were positively correlated with those at 30 cm (Figure 2b). Therefore, the decision was made to irrigate when the average readings in the control treatment exceeded 60 centibars, at which soil gravimetric water content was below 18%. However, due to water restrictions, this was not always possible.

Before applying fertiliser, bamboo leaves (youngest fully expanded leaves from the youngest culms) were sampled for N concentration (Figure 3a) to determine the amount of N required to raise leaf N to 3% (Kleinhenz and Midmore 2002). Mineral fertiliser (N:P:K at approximately 4:1:4 – 4:1:3) was applied to match nutrient requirements as prescribed by the total N levels in leaf samples from the 1-year-old culms.

Fertiliser was applied to a 20 m^2 area centred on each clump. On several occasions, non-destructive measurements were also undertaken with a leaf chlorophyll meter (Minolta SPAD-502) to develop a relationship between SPAD readings and bamboo leaf N concentration (Figure 3b).

The schedule of the N fertiliser timing and rate is indicated in Figure 3a.

Leaf N concentrations differed slightly between clumps before the fertiliser application so the absolute amount of N applied to raise leaf N concentration to 3% differed slightly between treatments.

Clump light interception was measured on some occasions with a line radiometer (AccuPAR Decagon Devices Inc., United States of America). Ten measurements were taken per clump, three each to the north and south of each clump and two to the east and west, between 11:00 and 13:00 h, and the average of readings was related to a concurrent reading with an exposed radiometer.

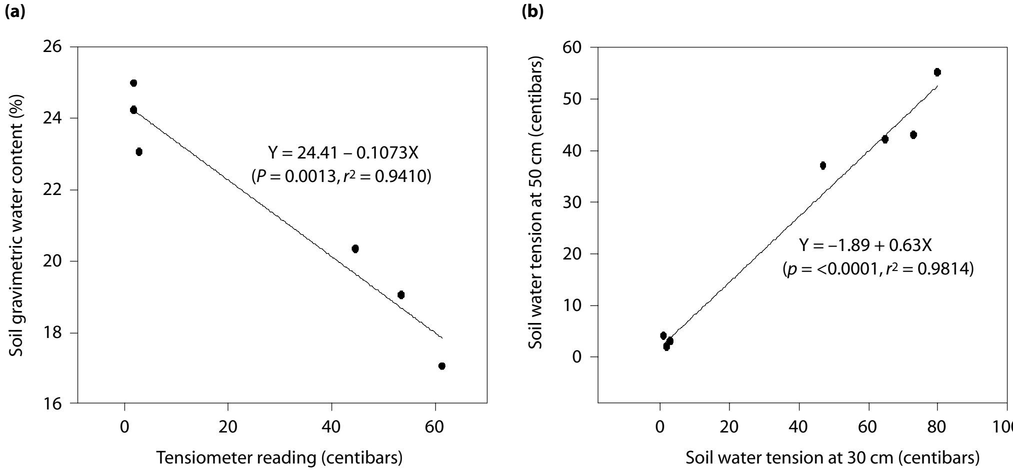

Figure 2. Relationship (a) between soil gravimetric water content and tensiometer readings and (b) between tensiometer readings at 30 cm and 50 cm depth

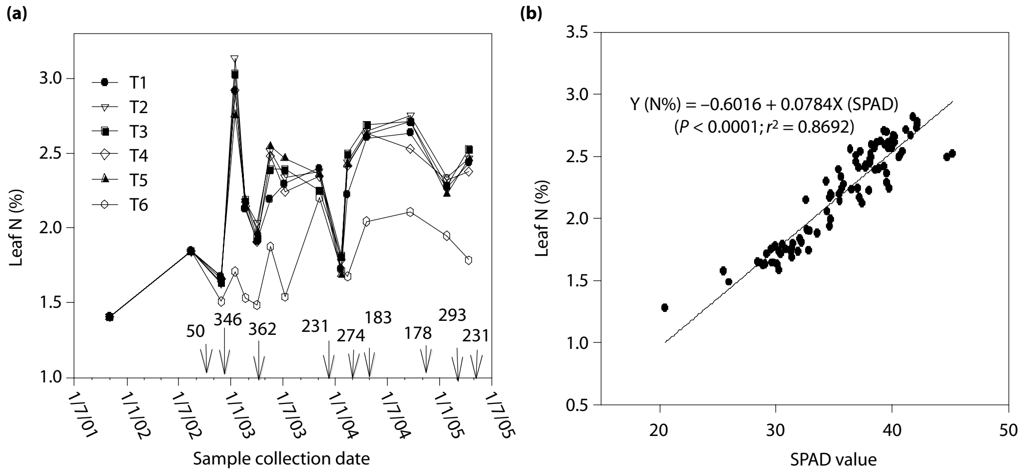

Figure 3. Bamboo leaf N concentration during 2002–05 (a) with related timing (with arrow down) and quantity (kg N/ha) of fertilisation, and (b) the relationship between leaf N concentration and soil plant analysis development (SPAD)

Shoots were harvested from January to March each year from 2003–05; total shoot numbers (including marketable, non-marketable and shoots for timber), and shoot marketable fresh weight (MFW) were recorded. Culms designated for harvest (i.e. those greater than 2 years old) were harvested in July 2003, August 2004 and October 2005. Numbers of culms and culm length from the base were recorded at culm harvest. Culm volumes (V) were calculated as shown in equation (1), according to the typical shape of the culm that is represented by a cylinder (cl) plus a cone (cn) (Figure 4) with the height of the cylinder (h_1) being two-thirds and that of the circular cone one-third (h_2) of the total height; and that the radius of the circular cone (r) two-thirds of basal radius (R) of the cylinder. This representation applies only to *Bambusa oldhamii* in the current experiment.

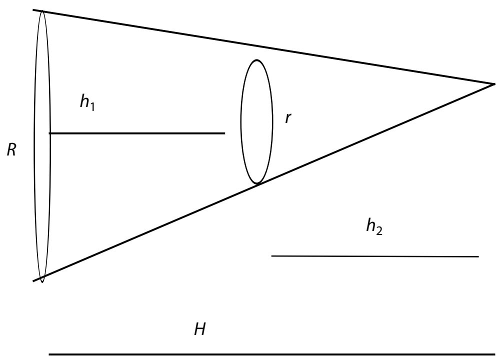

Figure 4. Estimation of bamboo culm general shape (see text for details)

In addition, to estimate total culm dry weight (DW), culms were sampled and sectioned to calculate the average apparent density according to the volumes (including the cylinder hole) and DW of each sample for each harvest/year (equation 2).

Data analysis and presentation

Water-use efficiency (WUE) was calculated based on total harvested fresh shoot or dry culm weights divided by the volume of water irrigated to each clump (water meters were inserted in-line to measure the amount of water applied to each treatment, and catch cans at the beginning of the experiment measured the volume applied to each clump) from the beginning of irrigation to the last irrigation, plus the amount of rain falling equally on each treatment during the same period, and assuming these amounts of water were fully available to plants. No account was made for run-off or drainage. Dry-season stress (T2) received less irrigation than T1 and T3–T5, and T6 (no irrigation) received rainfall only.

Nitrogen-fertiliser-use efficiencies (NFUEs) were calculated according to the total shoot and culm weights for each of five treatments (T1–T5) minus the total shoot and culm weights produced by T6 (unmanaged clump, not fertilised); with the differences divided by the N applied to each of the five treatments, respectively.

Analysis of variance with multiple comparisons (Systat Software, Inc. 2005, San Jose, California, United States of America) was used to determine significant differences among the treatments at P = 0.05. The analyses focused on differences between a specified treatment and the control with an orthogonal contrast test. When $0.05 < P < 0.1$, the differences between two treatments were discussed. Simple linear regressions were employed to define relationship between parameter pairs (e.g. culm and shoot production, WUE and NFUE).

The comparisons that showed trends between treatments and the differences between treatments within a season and across seasons are presented in Figures 5–13.

Converting shoot and culm production into a unified indicator for comparison

The aim of the experiment was to identify the best management practice to maximise edible shoot or timber production, or both. For the last, some treatments may produce more shoots, but fewer culms, creating difficulties for dual-purpose growers to identify the best treatment to maximise the gross margin. To address this problem, we introduced the productivity index (PI). The PI converts the DW of culms into shoot MFW equivalency, assuming the unit values of culm DW vary, ranging from one-tenth to unity of the value of shoot MFW (equation 3).

Assuming $K = 1$, and n = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1, respectively, PI can be calculated according to each n value based on the shoot MFW and culm DW harvested, and the differences between treatments can be compared according to the differences between the unified PI. This equation can be applied to bamboo growers for any of the three defined purposes: for shoot-only, n should be equal to or greater than 0, so the value of culm DW is negligible; and for culm-only, n can be still equal to, or smaller than K, since the production of MFW is negligible.

The differences of WUE and NFUE for shoot and culm production can similarly be compared between treatments by converting WUE and NFUE to the related PI, i.e. PI-WUE and PI-NFUE (equations 4 and 5).

Validation

To verify comparisons of PIs between treatments, real prices of shoots and culms from the experimental site were adopted. Bamboo shoot prices (D.L. Dart, Sole Director, Bamboo Australia Pty Ltd, pers. comm. 2006) varied from A$8.50/kg in November–December to A$3.50/kg in February–March of the following year and averaged A$6.00/kg; and the price of natural poles (culms) was roughly $2.76/kg (Bamboo Australia 2007). We used a value of $90.00/t ($n < 0.1$) payable for bamboo use for sequestering C or for pulp in calculations and comparisons of gross margins between treatments.

Results

Growth status and related water and nitrogen supply

Ground cover

Changes of groundcover over time, represented by light interception, reflected imposed treatments and culm harvesting (Figure 5). Following culm harvest on the afternoon of 8 July 2003, light interception was reduced in all treatments except for the unmanaged clump (T6). It was further reduced in T1, T2 and T3 between July 2003 and January 2004, whereas it increased over the same period in T4 and T5. Over the next 7 months, it increased to approximately the same value as in July 2003, and the treatments' values remained in the same order.

Soil water

Soil water was monitored with tensiometers in the control (T1) and the unmanaged clump (T6) treatments, and soil water content averaged for 15, 30 and

$$
\begin{aligned}
V &= vcl + vcn \\
vcl &= 1/3\pi\,(r^2 + rR + R^2)\,h_1 \\
vcn &= 1/3h_2r^2\,\pi \\
V &= 1/3\pi\,(r^2 + rR + R^2)\,\mathrm{h}_1 + 1/3h_2r^2\,\pi \\
&= 1/3\pi\,[(r^2 + rR + R^2)\,\mathrm{h}_1 + h_2r^2] \\
\text{As } r &= 2/3R;\ \text{and } h_1 = 2/3H;\ \text{and } h_2 = 1/3H,\ \text{Therefore:} \\
V &= 1/3\pi\,[((4/9R^2 + 2/3R^2 + R^2)*2/3\mathrm{H}) + 1/3H*4/9R^2] \\
&= 1/3\pi\,[(19/9R^2*2/3H) + (1/3H*4/9R^2)] = 14/27*H*R^2*\pi
\end{aligned}
\tag{1}
$$

$$
\text{DW (kg/clump)} = \text{Volume of culms harvested } (\mathrm{m^3/clump}) \times \text{apparent density of sampled culm } (\mathrm{kg/m^3}) \tag{2}
$$

$$
\text{PI (A\$/clump)} = K * \text{shoot MFW} + n * \text{culm DW} \tag{3}
$$

where the K is the value of unit shoot MFW and n is value of culm unit DW.

$$
\text{PI-WUE (\$/kg/mm)} = K * \text{WUE for shoot MFW} + n * \text{WUE for culm DW} \tag{4}
$$

$$
\text{PI-NFUE (\$/kg/kg)} = K * \text{NFUE for shoot MFW} + n * \text{NFUE for culm DW} \tag{5}
$$

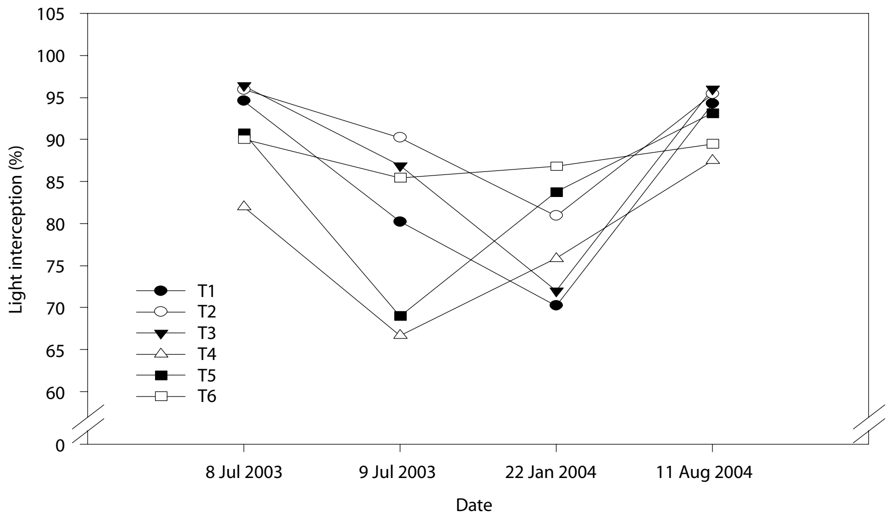

Figure 5. Light interception by bamboo clumps during the treatment period of 2003–04. Note: see Table 1 for treatment details.

50 cm (Figure 6) showed that the unmanaged clump (without irrigation) suffered water stress compared to the control (with irrigation) in 2002 when irrigation was available. In subsequent years drought prevented full application of irrigation water. Even with irrigation, plants suffered water stress at times in November and January due to high temperatures that led to high evapotranspiration. This was more apparent in 2002 and 2003 (Figure 6a and b) when the rainfall was very low (Figure 1) and relative humidity low. Control clumps also had very limited soil moisture during the dry season in 2004 and 2005 (Figure 6c and d) when irrigation was not sufficient due to water restrictions.

Leaf nitrogen concentration

The leaf nitrogen (N) concentration of the unmanaged clump (T6) was lower than that of other treatments on most occasions (Figure 3a). For all treatments the N concentration was relatively low during January–March compared to other periods probably due to the dilution effect of culm and leaf expansion, although this response was less apparent in 2005 (Figure 3a). Fertiliser application clearly increased leaf N concentration; for example, the leaf N concentration for the fertilised treatments reached 3% in January 2003 following application of 346 kg N/ha in late December 2002, but the N level dropped to below 2% in early January 2004 even after application of 231 kg N/ha in December 2003, most likely due to the exceedingly dry conditions, for we have shown (Kleinhenz et al. 2003) that for bamboo to respond to N fertiliser, supply of water—whether from irrigation or rainfall—is essential.

The leaf N concentration was closely related to measures of leaf chlorophyll concentration indicated by the readings of SPAD (Figure 3b), and the latter is simple and cheaper than wet chemistry determinations and, at least in the 1.5–3% N concentration range critical to plant N nutrition, can act as a surrogate for leaf N when determining the timing and quantity of N fertiliser.

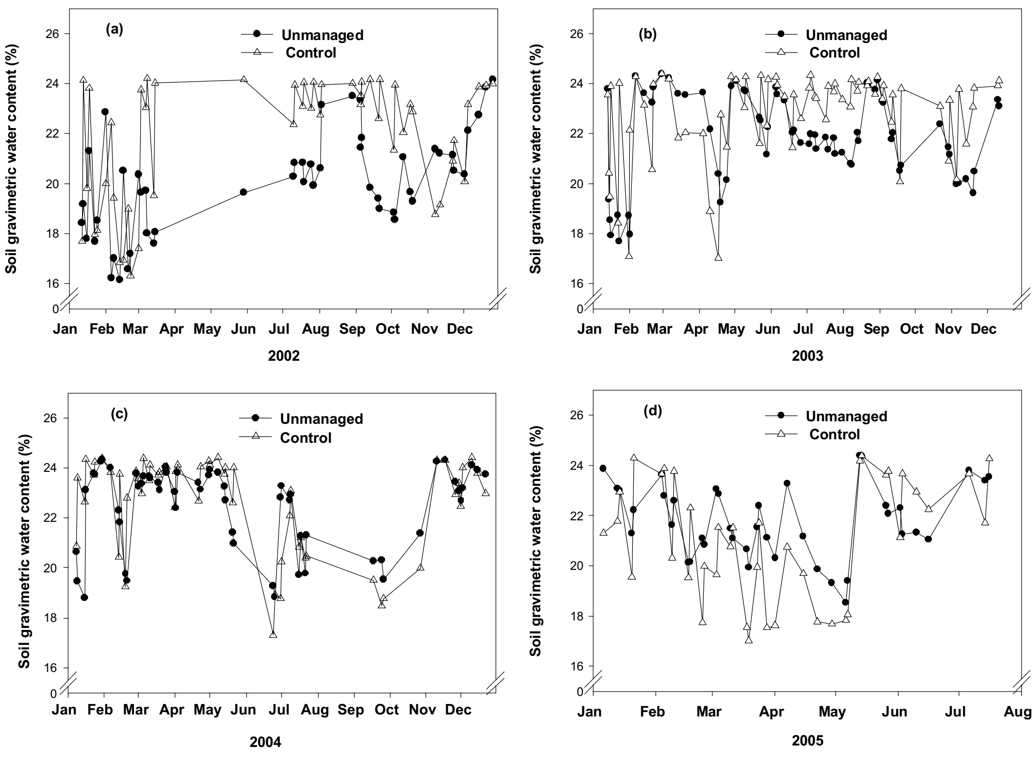

Figure 6. Average soil water status (0–50 cm) monitored by tensiometers for two selected treatments during 2002–05

Comparisons of bamboo shoot production

Shoot production within a season

As the period November–April is normally the rainy summer season in Queensland, bamboo shoots can be harvested from untreated clumps starting from January. Following 1 year of imposed treatments, the bamboo shoots were harvested from January 2003, and again in 2004 and 2005 over the same period. Within the harvest season in 2003, treatments T1, T2 and T4, i.e. those in which shoots were left for culm production early in the shoot season, produced more early shoots per clump than those of T3, T5 and T6 (Figure 7a). However, T3 became more productive later in the season, but both T5 and T6, i.e. those with rhizome stress or unmanaged, consistently produced fewer shoots (Figure 7a).

For marketable fresh weight (MFW), there was a greater proportional difference between treatments than for shoot number, with T3 constantly superior to other treatments (Figure 7b), reflecting greater individual shoot weight for that treatment.

The advantages of T3 were still evident in 2004 for both shoot number and weight per clump (Figure 8). It is interesting to note that the unmanaged treatment (T6) produced many shoots from February 2005 onwards (Figure 9a), but their size was not marketable (Figure 9b). In addition, T1, the control, caught up with, and surpassed, other treatments in shoot number and shoot MFW (Figure 9) from February 2005 onwards.

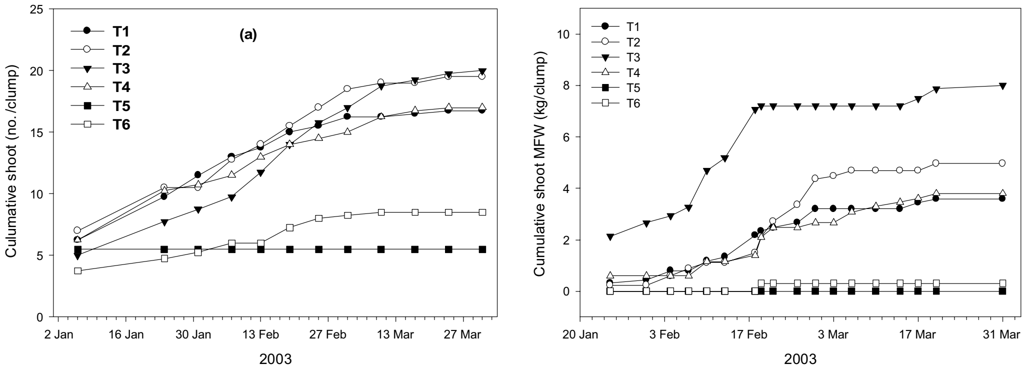

Figure 7. Seasonal cumulative bamboo shoot production in (a) number and (b) marketable fresh weight (MFW) in 2003. Note: see Table 1 for treatment details.

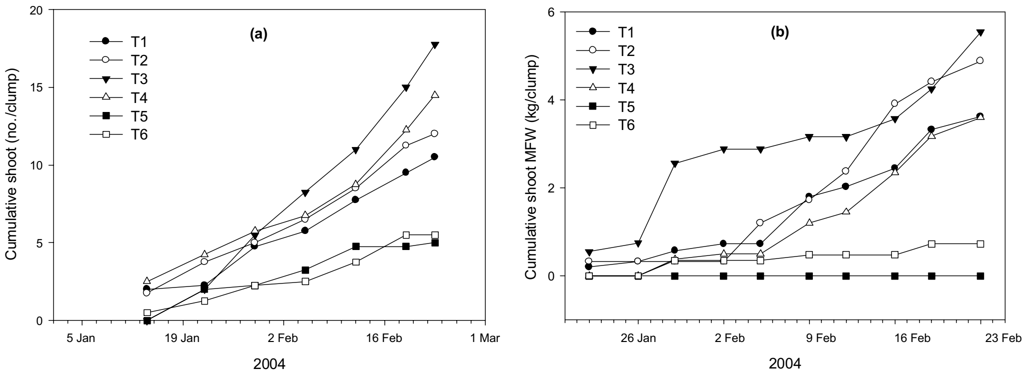

Figure 8. Seasonal cumulative bamboo shoot production in (a) number and (b) marketable fresh weight (MFW) in 2004. Note: see Table 1 for treatment details.

Shoot production across seasons

The annual shoot number for T3, the late-season selection of shoots for culms, was quite steady across the three harvest seasons (Figure 10a), but its ability to produce marketable shoots declined with each year (Figure 10b). There was a great increase in shoot numbers produced by T5 and T6 in 2005, but T6 did not produce many marketable shoots across the 3 years, and T5 produced a similar quantity of marketable shoots compared to T1, T2, T3 and T4 only in 2005 (Figure 10b).

Analysis of the cumulative shoot production, whether number or MFW across the 3 years, showed that T3 was superior to other treatments, particularly to T5 and T6 (Figure 11).

In summary, the best treatment for bamboo shoot production was the late-season selection (T3), and the worst treatments were rhizome stress (T5) and unmanaged clumps (T6). Other treatments, such as dry-season stress (T2) and narrow spacing (T4) were similar to the control in shoot production. Compared to T1 (control), the superiority of the T3 was verified through statistical analysis (Table 2) for both shoot number and shoot MFW.

Comparisons of bamboo culm production

Compared to the control and other treatments, the rhizome-stress treatment (T5) showed the greatest culm number in the first 2 years (Figure 12). This reflected that in T5, a number of culms less than

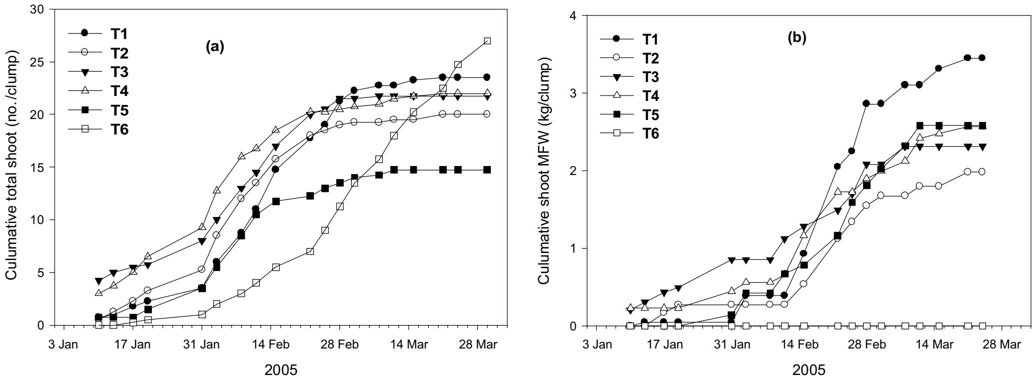

Figure 9. Seasonal cumulative bamboo shoot production in (a) number and (b) marketable fresh weight (MFW) in 2005. Note: see Table 1 for treatment details.

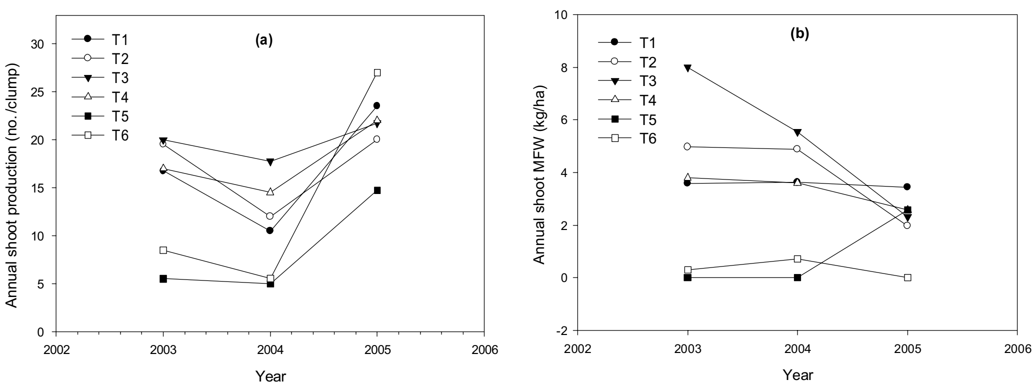

Figure 10. Annual bamboo shoot production in (a) number and (b) marketable fresh weight across 2003–05. Note: see Table 1 for treatment details.

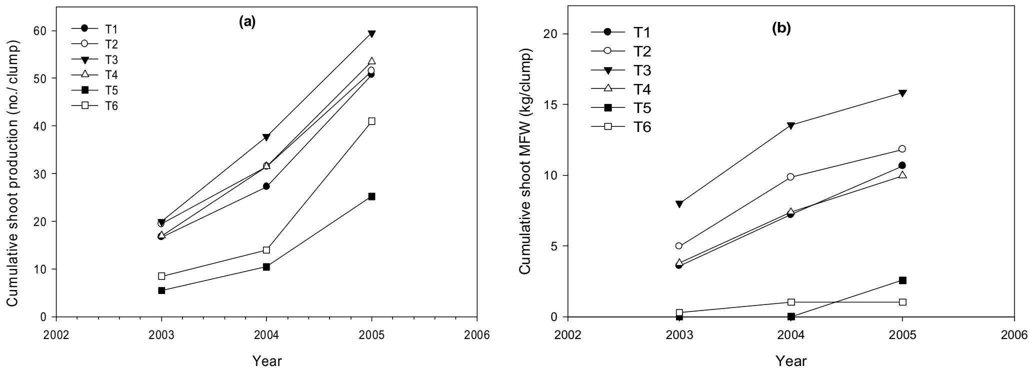

Figure 11. Cumulative bamboo shoot production in (a) number and (b) marketable fresh weight (MFW) across 2003–05. Note: see Table 1 for treatment details.

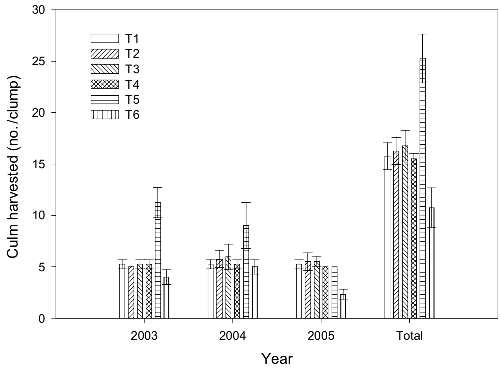

Figure 12. Yearly (2003, 2004 and 2005) and total culm number harvested. Note: see Table 1 for treatment details.

Table 2. Comparison of bamboo shoot production between the late-season selection (T3) and control (T1) across 2003–05

Treatment	Shoot number[a] (no./clump)				Marketable fresh weight (kg/clump)			
	2003	2004	2005	Total	2003	2004	2005	Total
Control	13.7	6.0	6.8	26.5	3.59	3.63	2.17	9.39
Late-season selection	15.4	15.7	12.8	43.9	8.00	5.55	2.31	15.86
P	0.400	**<0.0001**	**0.0712**	**0.0092**	**0.0031**	0.1571	0.8777	**0.0003**

[a] Shoot number includes marketable and non-marketable shoots, excluding shoots left to develop into culms

1 year old were also harvested—those culms being the ones left on the clump to 'stress' the rhizome. In the third year, edible shoots were harvested (to see if the rhizome had been 'stressed'), and therefore only five 3-year-old culms were harvested for biomass. Culm DW and volume per clump were also the greatest for T5 and, on average, least for T6 (Table 3). Compared to the control, T5 had 43.2% more culm dry matter in 2003, 98.3% in 2004, and 46.0% in total, and culm volume was greater by 43.2%, 98.3% and 47.2%, respectively (Table 3).

Table 3. Comparison of dry weight (DW; t/ha) and volume (m^3/ha) of bamboo culms harvested in July 2003, August 2004 and October 2005, and total, among the treatments

Treatment	2003		2004		2005		Total	
	DW	Volume	DW	Volume	DW	Volume	DW	Volume
T1	**24.15**	**61.52**	**23.70**	**55.28**	**25.57**	**55.00**	**73.42**	**171.80**
T2	19.95	50.84	24.84	57.96	30.78	66.20	75.57	175.00
T3	20.72	52.80	26.27	61.28	20.50	44.12	67.49	158.20
T4	19.18	48.88	28.32	66.04	24.05	51.72	71.55	166.64
T5	**34.59****	**88.12****	**46.99****	**109.60****	25.64	55.16	**107.22***	**252.88***
T6	**16.17****	49.40	26.24	61.20	**6.36****	**13.68****	**48.77***	**124.28+**
P	**0.0002**	**0.0009**	**0.0016**	**0.0016**	**0.0059**	**0.0059**	**0.0069**	**0.0120**

Note: + = 0.1 > *P* > 0.05; * = 0.05 > *P* > 0.01; ** = 0.01 > *P* > 0.001, compared to the control; see Table 1 for treatment details

Relationships between shoot and culm production

No clear relationship was detected between the number of shoots produced and the shoot MFW either within a year or across the 3-year shoot production period. This is understandable as some shoots harvested were not marketable (particularly in T6), and some shoots were counted but retained for culm production.

Similarly, on a per clump basis, no relationship was found between shoot MFW and culm production (neither culm dry matter nor volume), indicating that limited shoot harvest for consumption may have minimal impact on culm production. However, the relationship between shoot number and culm volume was negative (culm volume = 0.5538 – [0.0028 × shoot number harvested]), but barely significant ($P = 0.053$) and only explained 15% for the variation in culm volume. Therefore, excessive shoot harvest in terms of number may have some negative, but small effects on culm production.

WUE, NFUE and their relationships

Consideration of the efficiency in using soil water (from rainfall and irrigation) for shoot production showed that T2 (dry-season stress—no irrigation in the dry season) and T6 (unmanaged clump—no irrigation) had higher WUE than the control when based upon the total number of shoots produced (Table 4). The higher WUE for T6 was due to the sharp increase

Table 4. Comparisons of water-use efficiency (WUE) for both shoot and culm production between the control (T1) and other treatments during 2003–05

Treatment[a]	Total shoots produced[b] (no./mm/ha)	Shoots harvested[c] (no./mm/ha)	Shoot fresh weight[d] (kg/mm/ha)	Culm dry weight (kg/mm/ha)	Culm volume (cm^3/mm/ha)
T1	**2.28**	**1.13**	**0.37**	**8.48**	**19,828**
T2	**2.85+**	1.45	**0.58****	10.64	24,672
T3	2.74	**1.88***	**0.68****	7.80	18,256
T4	2.40	1.28	**0.46+**	7.64	17,788
T5	**1.11****	**0.46***	**0.12****	**11.48***	**27,056***
T6	**3.26***	**0.42***	**0.08****	9.20	23,500
P	**0.0049**	**0.0002**	**<0.0001**	**0.0671**	**0.0640**

[a] See Table 1 for treatment details
[b] Including shoots for culm production
[c] Including marketable and non-marketable shoots
[d] Marketable shoots only

Notes: 1 mm/ha = 10 m^3 and represents the amount of water received from rain and irrigation; + = 0.1 > *P* > 0.05; * = 0.05 > *P* > 0.01; ** = 0.01 > *P* > 0.001, compared to the control (T1) of shoot number produced in 2005 (see Figure 10a). However, based upon the marketable shoot weight, T2 (dry-season stress) and T3 (late-season selection) had higher WUE than the control, and T5 and T6 were lower than the control. No significant difference was detected between T2 and T3 ($P = 0.1005$). Although T5 (rhizome stress) had lower WUE than the control in shoot production, it had the highest WUE in culm production (dry weight and volume), and was the only treatment that differed significantly from the control in culm WUE.

As for WUE based upon shoot fresh weight, compared to the control, T2 and T3 had greater NFUE for shoot production (particularly in shoot MFW), and T5 had the lowest NFUE in shoot production, but the highest NFUE in culm production (Table 5).

A positive and linear regression was identified between WUE and NFUE for both shoot (Figure 13a) and culm (Figure 13b) production; an increase of WUE could lead to an increase of NFUE in bamboo production.

Identifying the best treatments according to the productivity index (PI)

According to the data, the late-season culm selection (T3), when compared to the control, produced more shoots in number and MFW (Figure 11, Table 2) without compromising culm production (Table 3). The rhizome-stress treatment (T5) produced more culm in terms of total volume and dry weight, but its production of marketable shoots was negligible compared to the control.

Table 5. Absolute differences between treatments T1–T5 and T6 (unmanaged clump as a contrast using t-test) for the calculations of nitrogen-fertiliser-use efficiency (NFUE) for shoot and clump production[a]

Treatment[b]	Total shoots produced[c] (no./kg)	Shoots harvested[d] (no./kg)	Shoot fresh weight[e] (kg/kg)	Culm dry weight (kg/kg)	Culm volume (cm^3/g)
T1	**1.98**	**4.42**	**1.65**	**14.95**	**29.0**
T2	2.26	4.83	**2.22+**	16.61	31.60
T3	**4.25+**	**8.21***	**3.16****	11.53	21.1
T4	2.38	4.81	1.93	9.99	17.4
T5	**–3.99****	**1.06***	**0.37****	**30.24***	**65.9***

a All values are given per weight of fertiliser N
b See Table 1 for treatment details
c Including shoots for culm production
d Including marketable and non-marketable shoots
e Marketable shoots only
Note: + = $0.1 > P > 0.05$; * = $0.05 > P > 0.01$; ** = $0.01 > P > 0.001$, compared to the control (T1)

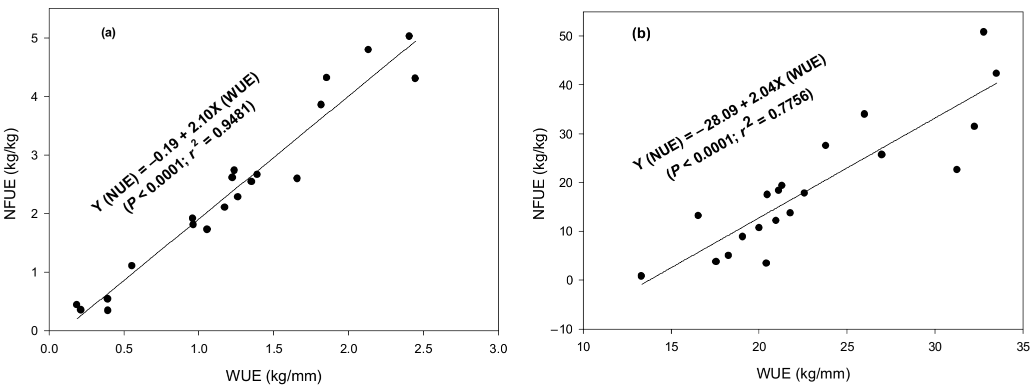

Figure 13. Regression analyses between nitrogen-fertiliser-use efficiency (NFUE) and water-use efficiency (WUE) for (a) shoot and (b) culm production

Using equation (3), the productivity index (PI) was calculated according to each *n* value (0.1–1.0) based on the total harvested shoot MFW and culm DW (Table 6). Recommendations can be made to bamboo growers that when the unit value of culm DW is one-tenth or less ($n \le 0.1$) that of shoot FW (e.g. at a market price of $6.00/kg for shoots, the price of culms would be ≤ $0.60/kg), T3 (late-season selection of shoots) is recommended for maximum gross margin; when the unit value of culm DW is the same as, or higher ($n \ge 1$) than that of shoot FW, T5 (rhizome stress) is recommended; when $1 > n > 0.1$, all treatments excluding T6 have similar economic impact; and under any circumstance, the T6 (unmanaged clump) is the worst treatment (Table 6).

However, if growers are constrained by water availability for shoot and culm production, the treatment that maximises the WUE and consequently gross margin is of interest to growers. Hence, according to equation (4), PI-WUE was calculated and compared between treatments (Table 7). According to the PI-WUE, when the culm value was one-tenth of shoot value, both T2 and T3 generated higher gross margin than the control (T1); however, T2 would be a preferred option for growers because it was less affected by changes of relative market values of shoot and culms, unless the value of culm was the same as the shoot ($n = 1$) when T5 showed the greatest advantage in gross margin (Table 7).

The same principle for PI-NFUE (equation 5) was also applied and compared among treatments. No significant difference in PI-NFUE was detected between treatments and the control unless the market value of unit culm DW was the same as that of shoot

Table 6. Comparisons of the productivity index[a] between treatments for the total harvested bamboo shoot and culm production (2003–05)

n	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
T1[b]	**25.03**	**26.93**	**33.60**	**36.88**	**41.25**	**47.37**	**56.54**	**71.84**	**102.43**	**194.20**
T2	27.11	28.99	35.45	38.82	43.32	49.62	59.07	74.81	106.30	200.76
T3	**32.74***	34.61	36.96	39.97	43.99	49.61	58.05	72.11	100.24	184.62
T4	26.51	28.35	30.65	33.60	37.54	43.06	51.33	65.12	92.70	175.42
T5	27.41	30.16	33.61	38.05	43.96	52.23	64.65	85.33	126.71	**250.84***
T6	**12.98****	**14.30****	**15.96****	**18.09****	**20.93****	**24.90****	**30.86****	**40.80****	**60.68***	**120.30***
df	13	13	15	15	15	15	15	15	15	15
P	**0.0003**	**0.0004**	**0.0056**	**0.0067**	**0.0080**	**0.0093**	**0.0104**	**0.0109**	**0.0105**	**0.0091**

[a] See text for details of how the productivity index was calculated

[b] See Table 1 for treatment details

Note: * = 0.05 > *P* > 0.01; ** = 0.01 > *P* > 0.001, compared to the control (T1); df = degrees of freedom

Table 7. Comparisons of the productivity index related to water-use efficiency (PI-WUE)[a] between treatments for bamboo shoot and culm production

n	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
T1[b]	**2.87**	**3.58**	**3.88**	**4.26**	**4.76**	**5.47**	**6.53**	**8.29**	**11.82**	**22.41**
T2	**3.83***	**4.63+**	**5.00+**	**5.47+**	**6.11+**	**7.00***	**8.33+**	10.55	14.99	28.31
T3	**3.78***	3.99	4.27	4.61	5.08	5.73	6.70	8.32	11.57	21.31
T4	3.06	3.27	3.54	3.88	4.33	4.97	5.92	7.52	10.70	20.25
T5	3.16	3.48	3.88	4.39	5.07	6.03	7.46	9.85	14.62	**28.95+**
T6	2.49	2.75	3.07	3.48	4.03	4.79	5.94	7.85	11.68	23.17
df	13	15	15	15	15	15	15	15	15	15
P	**0.0272**	**0.0735**	**0.0967**	0.1249	0.1557	0.1836	0.1999	0.1949	0.1646	0.1163

[a] Calculation was based on the WUE for shoot marketable fresh weight, plus WUE for culm dry weight at different *n* values (see text for further details)

[b] See Table 1 for treatment details

Note: * = 0.05 > *P* > 0.01; ** = 0.01 > *P* > 0.001, compared to the control (T1); df = degrees of freedom

FW, in which case T5 (rhizome stress) was the best treatment for maximal NFUE (data not presented), which is similar to the findings for WUE (Table 7).

Validation of the proposed PI models

The above models can be verified by entering the real prices of bamboo shoots and culms at the experimental site. For bamboo shoots, high (A$8.50/kg), low (A$3.50/kg) and medium prices (A$6.00/kg) were used for calculations, respectively; whereas for culms, two average prices were used (A$2.76/kg culm DW for high-value culms and A$90.00/t or A$0.09/kg if the culms were simply sold for C sequestration value or for pulp or energy generation), and the total gross revenues were calculated accordingly (Tables 8 and 9). The data in Table 8 including high-value culms fit the hypothesised PI model (Table 6) well, for the price ratios between culm DW and shoot FW were within the range of 0.1–1.0, and were 0.32, 0.46 and 0.79 at the given culm DW price of A$2.76/kg, when the shoot prices (A$/kg) were 8.5, 6.0, and 3.5, respectively. T5 always performed well, and better than T1 ($P = 0.07$), when the shoot price was low, whereas T4 performed poorly with the low shoot price. T6 performed poorly at any given price, and achieved only one-half of the gross margin of T5. However, statistically, T1, T2 and T3 were equally as good as T5 at any given shoot price.

When the lower price for bamboo culms ($0.09/kg, or $n = 0.03$ compared to the low shoot price, which is out of the predefined n range of 0.1–1.0) was used (Table 9), T3 was always superior to T4, T5 and T6 at any given shoot price, and outperformed T1 and T2 as well at high shoot price. This is the extreme case when bamboo growers cannot sell the culms for better prices.

The economic implications of Tables 8 and 9 are that when culms can be sold as a timber with an average price of A$2.76/kg, T1, T2, T3 and T5 are equally good and better than T6 at any given shoot price; whereas when the culms are sold for other uses with a low price, T3 showed the greatest advantage for any given shoot price.

Discussion

Bamboo is a perennial horticultural crop for shoot production, a timber source, an effective medium for C sequestration, and an energy source. Therefore,

Table 8. Calculation of gross margin (A$/clump) during 2003–05 based on shoot fresh weight with high (A$8.50/kg), medium (A$6.00/kg) and low (A$3.50/kg) prices, and culm dry weight at the average price of A$2.76/kg

Treatment	Shoot price	T1[A]	T2	T3	T4	T5	T6	df	*P*
Gross margin (A$/clump)	High	596.0 ab	620.3 ab	600.7 ab	541.5 ab	700.0 a	341.0 c	15	0.0107
	Medium	569.4 a	590.8 a	561.0 a	516.6 a	693.5 a	338.4 b	15	0.0106
	Low	542.8 ab	561.2 ab	521.4 ab	491.7 b	687.1 a	335.8 c	15	0.0095

[A] See Table 1 for treatment details

Note: Values followed by the same letter within a row are not significantly different at $P = 0.05$ according to Duncan's multiple range test; df = degrees of freedom

Table 9. Calculation of gross margin (A$/clump) during 2003–05 based on shoot fresh weight with high (A$8.50/kg), medium (A$6.00/kg) and low (A$3.50/kg) prices, and culm dry weight at the low price of $0.09/kg

Treatment	Shoot price	T1[A]	T2	T3	T4	T5	T6	df	*P*
Gross margin (A$/clump)	High	107.1 b	117.6 b	150.0 a	99.6 b	44.3 c	19.4 c	15	<0.0001
	Medium	80.5 ab	88.0 ab	110.4 a	74.7 b	37.8 c	16.9 c	15	<0.0001
	Low	53.8 ab	58.4 ab	70.7 a	49.8 b	31.4 c	14.3 c	15	<0.0001

[A] See Table 1 for treatment details

Note: Values followed by the same letter within a row are not significantly different at $P = 0.05$ according to Duncan's multiple range test; df = degrees of freedom bamboo should be managed with an integrated approach, both seasonally and yearly, for sustainable production. Accordingly, evaluation and comparison of the management effects should in part be based on the summed results across years.

The use of PI to unify the values of culm DW and shoot FW made it possible to compare the differences between treatments. Mathematically, the price ratios (n) between culm DW and shoot FW are not confined, but the hypothesised n range (0.1–1.0) is realistic, and provides the base on which growers can use the calculated PI table as a quick reference for their management decisions. When growers cannot sell their culms as timber at a good price, comparisons of gross margins between treatments were also made when culms were sold for other uses at a considerably lower price ($n < 0.1$).

When compared to the control treatment (i.e. designed with wide clump space, early selection of shoot for timber production, and with irrigation and fertilisation) which represents a conventional management practice for bamboo production, improved management practices can increase bamboo productivity, WUE and NFUE. Based on the current trials, the ideal improved treatments were T2 (dry-season stress), T3 (late-season selection) and T5 (rhizome stress), depending on the bamboo growers' intentions to maximise their gross margin. If a grower focuses on shoot production (or if the market value of culm per unit DW is much smaller than that of shoot per unit FW, e.g. $n \leq 0.1$) then T3 is the preferred choice; if the focus is on culm production, T5 is the preferred choice; and in most other instances, T2 is the preferred choice as it greatly increased WUE without compromising the combined values of shoot and culm production. The values for WUE (Table 4) at c. 10 kg/m^3 (or 1.0 g/kg) are intermediate to the range of values presented by Trebejo and Midmore (1990) for total dry weight of potato plants, but considerably lower than the 5.3 g/kg reported for willow by Linderson et al. (2007), although the latter values were based upon transpirational-use efficiency, not on total water-use efficiency.

If water were a limited resource and/or a paid-for commodity, T2 would be of particular interest. Declining agricultural supply of water necessitates the development of methods for efficient irrigation. In our research, bamboo with dry-season stress resulted in an average PI-WUE 29% higher than the control (Table 7). From a practical perspective, the management of dry-season stress in the present experiment is similar to that in rice production where alternate wetting and drying cycles, albeit on a much shorter time frame, in trials conducted in China and the Philippines, reported water savings of 13–30%, with no significant reduction in yield (Cabangon et al. 2001; Belder et al. 2002; Virk et al. 2004). Similar irrigation strategies, but again on a much shorter time frame, have been widely implemented in horticultural industries; for example, by adopting partial root drying which increases fruit quality and water-use efficiency by 50% (Stoll et al. 2000) to 80% (dos Santos et al. 2003) compared to full irrigation.

The physiological mechanism for the superiority of shoot production in T3 (late-season selection of shoots for timber production) is not clear; it may be that leaving early shoots for culm production inhibits further shoot production but this was not so in the NT (Traynor et al. 2009), or it may be that younger culms in the following season are more likely to support more shoots in that season.

The treatment T5, where essentially no shoots were removed as a vegetable, and culms less than 1 year of age and additional in number to the five to keep were harvested, had the highest timber production. The annual biomass removed (on average c. 20–45 t/ha) was comparable to other reports (Kleinhenz and Midmore 2001).

Nevertheless, in terms of financial suitability for growers, T3 may be the best option for generating stable income for growers regardless of fluctuations in the shoot and culm markets. These results are for *B. oldhamii* growing in southern Queensland. Recommendations should be considered and adapted according to different bamboo species and their growing conditions.

When the marketing value of the culm is low, the production of shoots is very important. To ensure sustainable bamboo growth status for shoot production, leaf N concentration should be monitored periodically to guide decisions for fertiliser application. However, growers cannot afford to have frequent chemical analysis of bamboo leaves upon which to base fertiliser decisions. Fortunately, our research showed that the use of a SPAD chlorophyll meter is a cheap and reliable surrogate to estimate leaf N concentration. However, meter measurements should be calibrated to leaf N concentration for each species and growing situation.

As the bamboo industry is still relatively new to Australia, economic analysis should be undertaken to assist growers to determine break-even prices for culms and shoots. This analysis will take into account the costs of irrigation, fertilisation and harvest, with or without hired labour. In this regard, this newly completed bamboo experiment can be subjected to further economic analysis.

References

Bamboo Australia 2007. Bamboo pole products. Bamboo Australia: Belli Park, Queensland. At: <http://www.bamboo-oz.com.au/pricepoles.html#POLES>. Accessed May 2007.

Belder P., Bouman B.A.M., Spiertz J.H.J., Lu G. and Quilang E.J.P. 2002. Water use of alternately submerged and nonsubmerged irrigated lowland rice. Pp. 51–61 in 'Water-wise rice production. Proceedings of the International Workshop on Water-wise Rice Production, Los Baños, the Philippines, 8–11 April 2002', ed. by B.A.M Bouman, H. Hengsdijk, B. Hardy, P.S. Bindraban, T.P. Tuong and J.K. Ladha. International Rice Research Institute: Los Baños.

Cabangon R.J., Castillo E.G., Bao L.X., Lu G., Wang G.H., Cui W.L., Tuong T.P., Bouman B.A.M., Li Y.H., Chen C.D. and Wang J.Z. 2001. Impact of alternate wetting and drying irrigation on rice growth and resource-use efficiency. Pp. 55–79 in 'Water-saving irrigation for rice. Proceedings of the International Workshop, Wuhan, China, 23–25 March 2001', ed. by R. Barker, R. Loeve, Y.H. Li and T.P. Tuong. International Water Management Institute: Colombo, Sri Lanka.

Dart D.L. 1999. The bamboo handbook—a farmers, growers and product developers guide. Nemea Pty Ltd: Brisbane, Australia.

Debaeke P., Rouet P. and Justes E. 2006. Relationship between the normalized SPAD index and the nitrogen nutrition index: application to durum wheat. Journal of Plant Nutrition 29, 75–92.

dos Santos T.P., Lopes C.M., Rodrigues M.L., de Souza C.R., Maroco J.P., Pereira J.S., Silva J.R. and Chaves M.M. 2003. Partial rootzone drying: effects on growth and fruit quality of field-grown grapevines (*Vitis vinifera*). Functional Plant Biology 30, 663–671.

Gáborccaroník N. 2003. Relationship between contents of chlorophyll (a+b) (SPAD values) and nitrogen of some temperate grasses. Photosynthetica 41, 285–287.

Kleinhenz V. and Midmore D.J. 2001 Aspects of bamboo agronomy. Advances in Agronomy 74, 99–153.

Kleinhenz V. and Midmore D.J. 2002. Improved management practices for culinary bamboo shoots. RIRDC Publication No. 02/035. Rural Industries Research and Development Corporation: Canberra.

Kleinhenz V., Milne J., Walsh K.B. and Midmore D.J. 2003. A case study on the effects of irrigation and fertilization on soil water and soil nutrient status, and on growth and yield of bamboo (*Phyllostachys pubescens*) shoots. Journal of Bamboo and Rattan 2, 281–293.

Lin Q.Y. 1996. Cultivation techniques for *Dendrocalamopsis oldhamii*. Pp. 50–55 in 'Bamboo, people and the environment. Proceedings of the Vth International Bamboo Workshop and the IVth International Bamboo Congress, Ubud, Bali, Indonesia, 19–22 June 1995', ed. By I.V.R. Rao and C.B. Sastry. International Network for Bamboo and Rattan: New Delhi.

Linderson M.L., Iritz Z. and Lindroth A. 2007. The effect of water availability on stand-level productivity, transpiration, water use efficiency and radiation use efficiency of field-grown willow clones. Biomass and Bioenergy 31, 460–468.

Monje A. and Bugbee B. 1992. Inherent limitations of nondestructive chlorophyll meters: a comparison of two types of meters. HortScience 27, 69–71.

Peng S., Garcia F.V., Laza R.C., Sanico A.L., Visperas R.M. and Cassman KG. 1996. Increased N-use efficiency using a chlorophyll meter on high-yielding irrigated rice. Field Crops Research 47, 243–252.

Stoll M., Loveys B. and Dry P. 2000 Hormonal changes induced by partial rootzone drying of irrigated grapevine. Journal of Experimental Botany 51(350), 1,627–1,634.

Traynor M. and Midmore D.J. 2009. Cultivated bamboo in the Northern Territory of Australia. In 'Silvicultural management of bamboo in the Philippines and Australia for shoots and timber', ed. by D.J. Midmore. ACIAR Proceedings No. 129, 108–123. [These proceedings]

Trebejo I. and Midmore D.J. 1990. The effect of drought on potato (*Solanum* spp.) growth, yield and water use in a hot and a cool tropical climate. Journal of Agricultural Science (Camb.) 114, 321–334.

Turner F.T. and Jund M.F. 1991. Chlorophyll meter to predict nitrogen topdress requirement for semidwarf rice. Agronomy Journal 83, 926–928.

Virk P., Virmani S.S., Lopena V. and Cabangon R. 2004. Enhancing water productivity in irrigated rice. In 'New directions for a diverse planet: Proceedings of the 4th International Crop Science Congress, Brisbane, Australia, 26 Sep – 1 Oct 2004'. The Regional Institute: Gosford (published online). At: <http://www.cropscience.org.au/icsc2004/poster/1/1/347_virka.htm>. Accessed 25 May 2008.

ACIAR

Research that works for developing countries and Australia

www.aciar.gov.au