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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

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Abstract—Bamboo is one of the world's most important and versatile crops, covering extensive areas, particularly in East and Southeast Asia. There is, however, rising concern about acute scarcity of bamboo products, among which are fresh edible vegetable shoots. Appropriate agronomy and crop management may play a key role in alleviating this situation. From 1994 to 1998, we studied the effects of irrigation and compound fertilizer application on soil water and soil nutrient status, and on growth and shoot yield of *Phyllostachys pubescens* established in 1990 in south-east Queensland, Australia. Water supply had a major effect on bamboo growth and shoot yield. Without irrigation and only little rainfall (80–140 mm) prior to and during the shoot season in the first 2 years of the study, shoot numbers were greater in plots closer to a supply of temporal pond water. Harvests were not made in those years. With irrigation in the following years, bamboo shoot numbers and individual shoot weights were much greater at the higher rate of irrigation. Bamboo marginally responded to increasing rates of fertilizer application; notable was the response when it was applied in the inorganic form and combined with the higher irrigation rate. Respective yields under these conditions were 8300, 10 200 and 14 200 kg ha^{-1} of shoots at 250, 375 and 500 kg N ha^{-1} year^{-1} applied as compound fertilizer with N : P : K ratio of 5 : 1 : 2.8. Leaf nitrogen also reflected the yield response to fertilizer, but soil nitrogen did not. Response to an organic (chicken dung) form of fertilizer, albeit providing approximately one half of the rate of inorganic fertilizer, was negligible.

Key words: Irrigation; fertilization; moso; growth; bamboo shoots.

INTRODUCTION

Over 70 genera of bamboo with over 1200 species cover an area of more than 14 million ha worldwide [1]. Of these species, *Phyllostachys pubescens* ('Moso') is the world's single most important, occupying about 2.3 million ha in China alone [2].

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Fresh, edible shoots are one of the main bamboo products with more than about 2 billion kg consumed globally per year [3]. There is rising concern about acute scarcity of bamboo products in the future [4]. For example, in India it is projected that at the current level of bamboo productivity for the paper industry, and with the growing demand for paper, an additional 30–60 million ha of land would be required by 2015 [5] to satisfy this demand. Better resource use and in particular suitable agronomic practices are given top priority [6] to satisfy the anticipated increasing future demand for bamboo products.

Precipitation affects distribution and limits growth of bamboo more than any other component of climate, except temperature [7]. In China, productivity of bamboo dramatically increases with annual rainfall [8]. The maximal annual evapotranspiration rate of bamboo has been estimated to be about 3300 mm (equivalent to 33 million $l\,ha^{-1}$) [9]. Introduction of irrigation could, therefore, improve production of bamboo products in areas without adequate amount and distribution of rainfall. To our knowledge, however, only very few studies have attempted to quantify water usage of bamboo under field conditions or to systematically test irrigation rates.

In contrast, much more research has been conducted on the response of bamboo growth and yield to application of nutrients, in particular N. Soil N availability is of great importance and fertilizer application can have dramatic impacts on bamboo growth and production of bamboo products [8]. Despite this knowledge, there is little information available on the effects of N supplements on bamboo shoot production under different rates of water availability.

The aims of this study, undertaken from 1994 until 1998 in a stand of *P. pubescens* at a commercial plantation in southern Queensland (Australia), were to quantify the effects of supplements of different rates of (1) water and (2) fertilizer on (a) soil water and soil N status, (b) plant water and plant N status and (c) growth and shoot yield and its components in bamboo.

MATERIALS AND METHODS

All experiments were conducted at a commercial bamboo farm ('Bamboo Australia') at Belli Park near Eumundi (26°28′ S, 152°56′ E), Queensland (Australia). Annual precipitation was 1476, 1491, 1347, 1240 and 1420 mm from 1994 to 1998, and daily evaporation during that time averaged 4.0 mm. Daily minimum and maximum temperature averaged 17 °C and 28 °C from October to March, and 10 °C and 23 °C from April to September. From 1994 to 1998, a total of 76, 137, 138, 158 and 237 mm of rainfall fell during the Sep.–Oct. shoot season of *P. pubescens*. Torrential rain occurred during the shoot season in 1997 and 1998 (Fig. 1), but not in 1996. The soil at the experimental site was a clay soil, moderately-to-strongly acid, with high levels of Mn and Al, but low in organic C, and in available N, P, and K (Table 1).

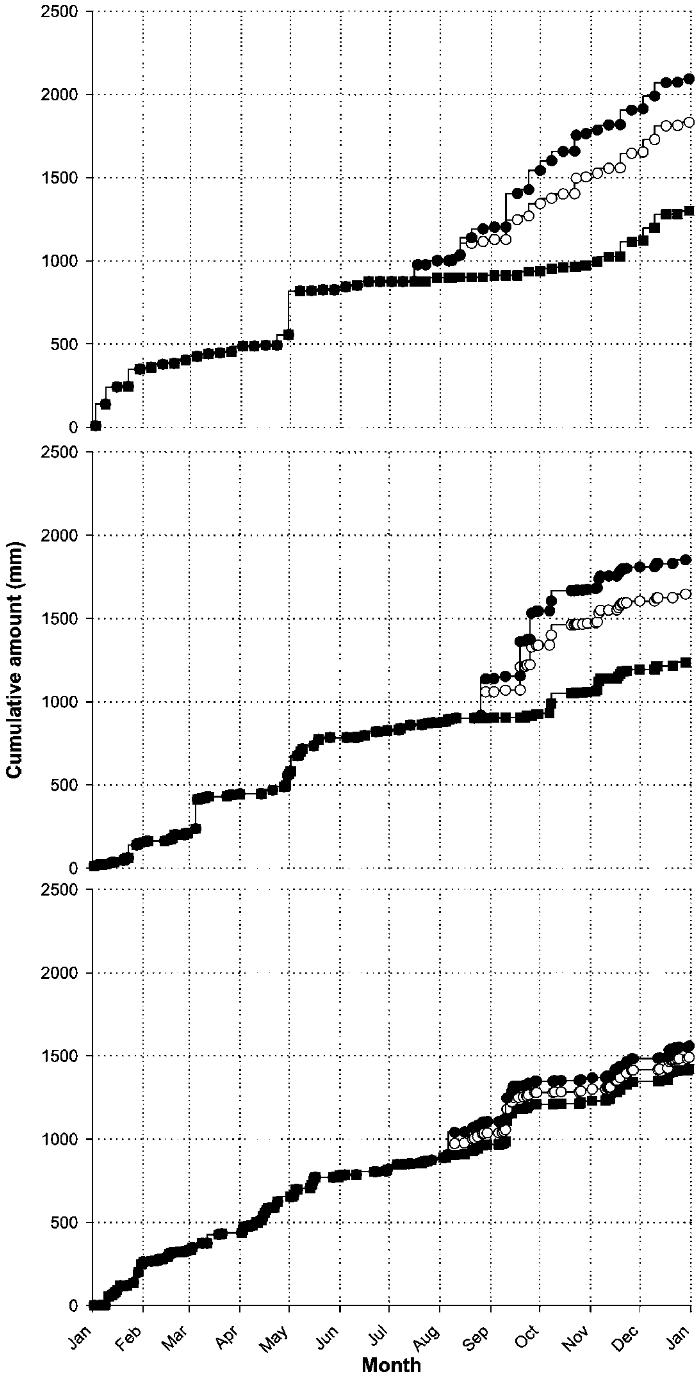

Figure 1. Cumulative amounts of water supplied by (●) precipitation and irrigation in the (❍) 'low-irrigation' and the (■) 'high-irrigation' treatments during 1996 (top), 1997 (middle) and 1998 (bottom).

Table 1.
Soil chemical characteristics (0–30 cm soil depth) at the experimental site at Belli Park in 1994

Soil characteristic	Value
pH ($CaCl_2$)	5.1
Organic C (%)	2.3
NO_3—N (ppm)	14
P (Bray) (ppm)	27
K (ppm)	36
Mn (ppm)	46
Al (ppm)	38

Plant material and experimental treatments

From 1994 through 1998, an existing stand of *P. pubescens* planted in 1990 at 7 m × 7 m (and in 1994 thinned to about 1 culm m^{-2} and 5–7-m-long culms) was split into two experimental areas to which different rates of irrigation ('low irrigation' and 'high irrigation') were applied. Both areas were located on a slightly sloping field (approx. 5%), with the low-irrigation area located at the lower part, 30 m from an adjacent temporal pond. Only total supply of irrigation water to the site was metered, but additional rotary sprinklers allowed 50% greater supply to the 'high irrigation' area. Due to water shortages in the region, irrigation treatments could not be imposed in 1994 and 1995, and only in August in 1998. From 1996, irrigation commenced about 1–2 months before the shoot season of bamboo, i.e. in Jul.–Aug. (Fig. 1) to provide approx. 10 mm day^{-1} until the end of the shoot season.

Individual irrigation areas were split into four replicate rows, running at right angles to the slope, with three plots along each row randomly assigned one of three N application treatments: (1) 'standard' rate, (2) 1.5 times the 'standard' rate and (3) 2.0 times the 'standard' rate. Each plot comprised a marked-out 49 m^2 area and fertilizer was applied by hand. From 1994 through 1996, the 'standard' rate was 250 : 50 : 141 kg N : P : K ha^{-1} $year^{-1}$ as inorganic compound fertilizer ('CK 120', Incitec Fertilizers, Mackay, Qld, Australia), and during 1997 and 1998 approximately 130 : 90 : 50 kg N : P : K ha^{-1} $year^{-1}$ (based upon chemical analyses) as composted chicken manure. These rates were applied in July before the shoot season.

Field methods

During late 1996, tensiometers ('Soilspec' tensiometer system, H&TS Electronics, Healesville, Victoria, Australia) were installed in the "1.5 × 'standard' rate" treatment of both irrigation areas and at two depths (30 and 60 cm) replicated four times in each irrigation area (one per 49 m^2). Readings were taken at approximately weekly intervals.

Leaf water potential was measured with a pressure bomb (Soilmoisture Equipment, Santa Barbara, CA, USA) in newly fully expanded bamboo leaves in the 1.5 × standard rate treatment of both irrigation areas on 25 October 1996 at 10:00, 14:00 and 18:00 hours with four replications.

Soil cores were sampled 0–30 cm deep across the experimental area with a punch tube (approx. 2.0 cm diameter) before applying treatments in 1994. Soil was again sampled and four newly expanded bamboo leaves collected in every experimental plot of the high-irrigation area in October 1996. Soil and plant samples were dried for 48 h at 65°C and analysed at a laboratory (Incitec Fertilizers, Gibson Island Laboratory, Murarrie, Queensland, Australia).

Bamboo shoots are produced annually by the perennial bamboo species, in what we term the 'shoot season', which may span over 4–6 weeks in some species to 10–12 weeks in others. Numbers of new bamboo shoots were recorded during 1994–1998 for individual experimental plots at approximately 5-day intervals. In addition, from 1996–1998 shoots were harvested and their individual weight was recorded. New shoots were not harvested before 1996, to hasten achievement of full canopy.

Since not replicated, differences between irrigation treatments were compared with standard errors (SE) across fertilizer application treatments ($n = 12$) with the exception of tensiometer and leaf water potential readings for which $n = 4$. Differences between levels of N application treatments were analysed as single-factor experiments at each irrigation level ($n = 4$) with ANOVA, and means separated with the LSD test ($P = 0.05$). Data were analysed with SAS for Windows Version 6.12 [10].

RESULTS

Soil water and leaf water status

Figure 2 shows soil moisture tension at 30- and 60-cm depth for the two irrigation areas during 1997. In contrast to those at 30-cm soil depth (−33±3.5 and −38±3.5 kPa), annual averages for soil moisture tension at 60-cm soil depth were significantly different between low-irrigation (Fig. 2a) and high-irrigation (Fig. 2b) area (−30±3.5 and −40±3.9 kPa, respectively). This indicated greater supply of underground water to the low-irrigation area. Averages for the period from after the heavy rain in May until irrigation was applied in July were significantly different between low-irrigation and high-irrigation area at both soil depths (30-cm depth: −15±3.3 and −23±3.6 kPa; 60-cm depth: −13±2.8 and −25±4.6 kPa, respectively). This indicated greater water use by the crop in the high-irrigation area, rather than more rapid drainage since soil water tension in both areas had reached values corresponding to field capacity (when drainage essentially ceases).

Data for leaf water potential were collected after a week with only 5 mm of precipitation, but 141 and 94 mm of irrigation had been applied in the high-irrigation and low-irrigation areas. Although significant only in the afternoon (14:00

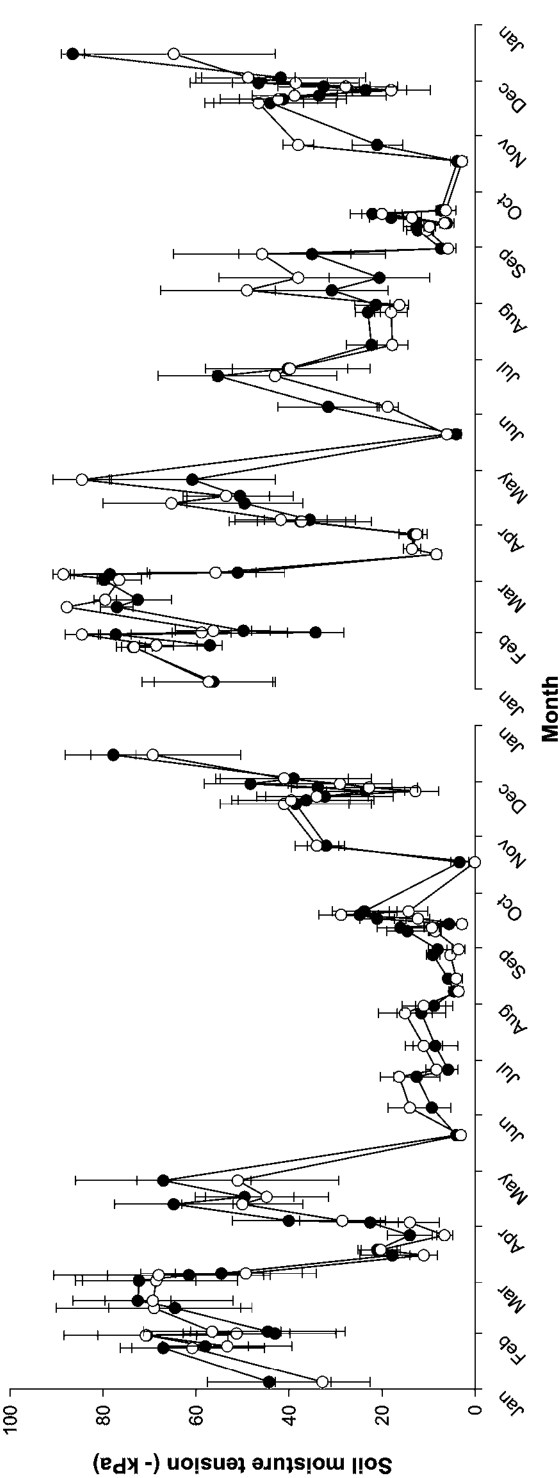

Figure 2. Soil moisture tension at (●) 30-cm and (○) 60-cm soil depth in the (left) 'low-irrigation' and (right) 'high-irrigation' treatment in 1996. Vertical bars represent SE.

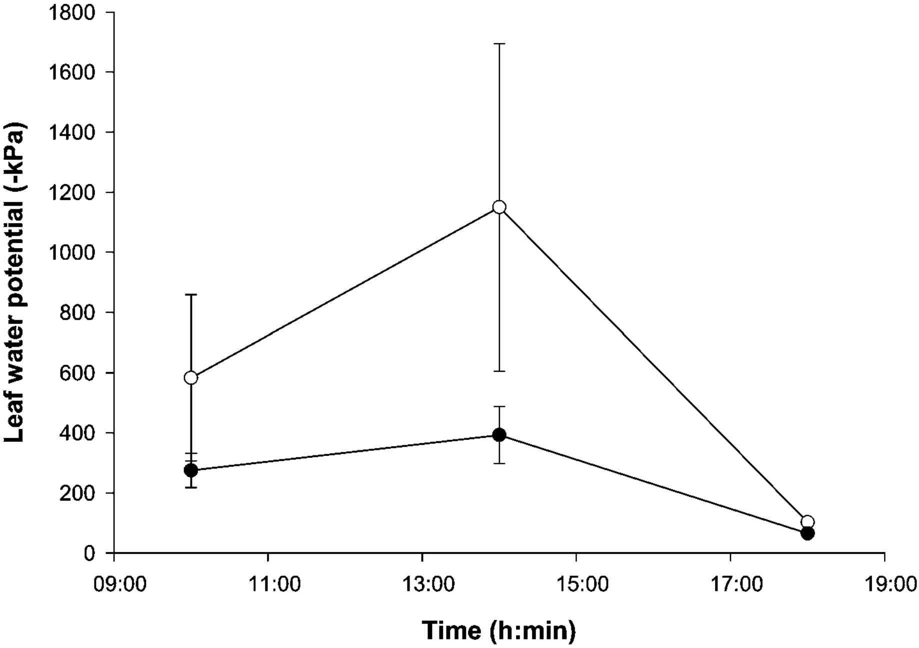

Figure 3. Leaf water potential in youngest fully expanded leaves of bamboo plants in the (❍) 'low-irrigation' and the (●) 'high-irrigation' treatments on 25 October 1996. Vertical bars represent SE.

hours), leaf water potential was greater (i.e. less negative) in the 'high-irrigation' area (Fig. 3). This corresponded to soil moisture tension at 30-cm depth, which was significantly ($P < 0.10$) greater in that area (-21 ± 5.4 kPa) than in the low-irrigation area (-32 ± 4.0 kPa). Soil moisture tension at 60-cm soil depth was not significantly different (high-irrigation area: -38 ± 3.3 kPa; low-irrigation area: -34 ± 4.7 kPa).

Soil N and leaf N status

After three years of N application, soil N was not significantly different between N application rates in the high-irrigation area (Table 2). In contrast, leaf N increased significantly with higher N rates. All leaf N concentrations were much greater compared with a nearby non-fertilized bamboo stand (1.70 ± 0.054% N).

Bamboo growth, yield and components of yield

Generally, the number of new bamboo shoots each year increased over 1994 to 1996, but decreased thereafter. The irrigation treatments had a much greater effect on bamboo production than did the fertilizer application treatments. Although no irrigation was applied in 1994 or 1995, more new shoots emerged in bamboo in the low-lying area assigned for the low-irrigation treatment during 1994 and 1995 (Table 3). This was statistically significant in 1995. The number of (harvested)

Table 2.
Effect of fertilizer rate (1.0, 1.5 and 2.0 times standard rate) on total soil N (0–30 cm soil depth) and leaf N in *P. pubescens* ('high-irrigation' area) at Belli Park in 1996

Fertilizer rate (×standard)	Soil N (%)	Leaf N (%)
1.0	0.144 ± 0.0078[a]	3.04 ± 0.095
1.5	0.143 ± 0.0098	3.19 ± 0.037
2.0	0.144 ± 0.0093	3.37 ± 0.072

[a] Standard rate = 250 : 50 : 141 kg ha^{-1} year^{-1} N : P : K during 1994–1996. Values are mean ± standard error (SE).

Table 3.
Effect of irrigation rate (low, high) and fertilizer rate (1.0, 1.5 and 2.0 times standard rate) on total number of new shoots (shoots ha^{-1}) of *P. pubescens* at Belli Park from 1994 to 1998

Year	Irrigation rate											
	Low						High					
	Fertilizer rate (× standard rate)			LSD	Mean	SE[a]	Fertilizer rate (× standard rate)			LSD	Mean	SE
	1.0	1.5	2.0				1.0	1.5	2.0			
1994	60 000	43 900	31 400	n.s.	55 200	5400	50 700	65 700	49 300	n.s.	45 000	6220
1995	97 100	100 000	76 100	n.s.	85 400	11 200	50 700	68 600	55 700	n.s.	58 300	4790
1996	43 700	47 000	59 700	n.s.	50 200	13 500	90 100	75 200	104 500	20 468*	89 900	4910
1997	13 900	15 100	13 200	n.s.	14 100	1600	20 900	27 500	27 800	n.s.	25 400	2420
1998	2900	3800	3500	n.s.	32 300	500	4800	4500	4600	n.s.	4600	560

[a] Standard rate = 250 : 50 : 141 kg ha^{-1} year^{-1} N : P : K during 1994–1996 and approx. 130 : 90 : 50 kg ha^{-1} year^{-1} N : P : K during 1997–1998. LSD = least significant difference between fertilizer rates under low and high irrigation. SE = SE of low- and high-irrigation treatments. n.s., not significant at $P = 0.05$; *significant at $P = 0.05$.

shoots in the 'high-irrigation' area, however, significantly exceeded that in the 'low-irrigation' area after 1995 when irrigation was applied. Fertilizer application treatments had no significant effect on shoot numbers in the 'low-irrigation' area throughout the study period. This was so for the 'high-irrigation' treatment except in 1996 when the number of new shoots in the '2.0 × standard rate' treatment significantly exceeded that in the '1.5 × standard rate' treatment (Table 3).

Figure 4 presents cumulative shoot yields in the two irrigation areas over each of the shoot seasons from 1996 to 1998. These data reflect data for number of shoots (Table 3); bamboo in the high-irrigation area significantly out-yielded those in the low-irrigation area in all years due to a greater number of shoots (Table 3) and greater individual shoot weight (Table 4). Higher fertilizer application improved shoot yields only in 1996 in the high-irrigation area. This was due to a significantly

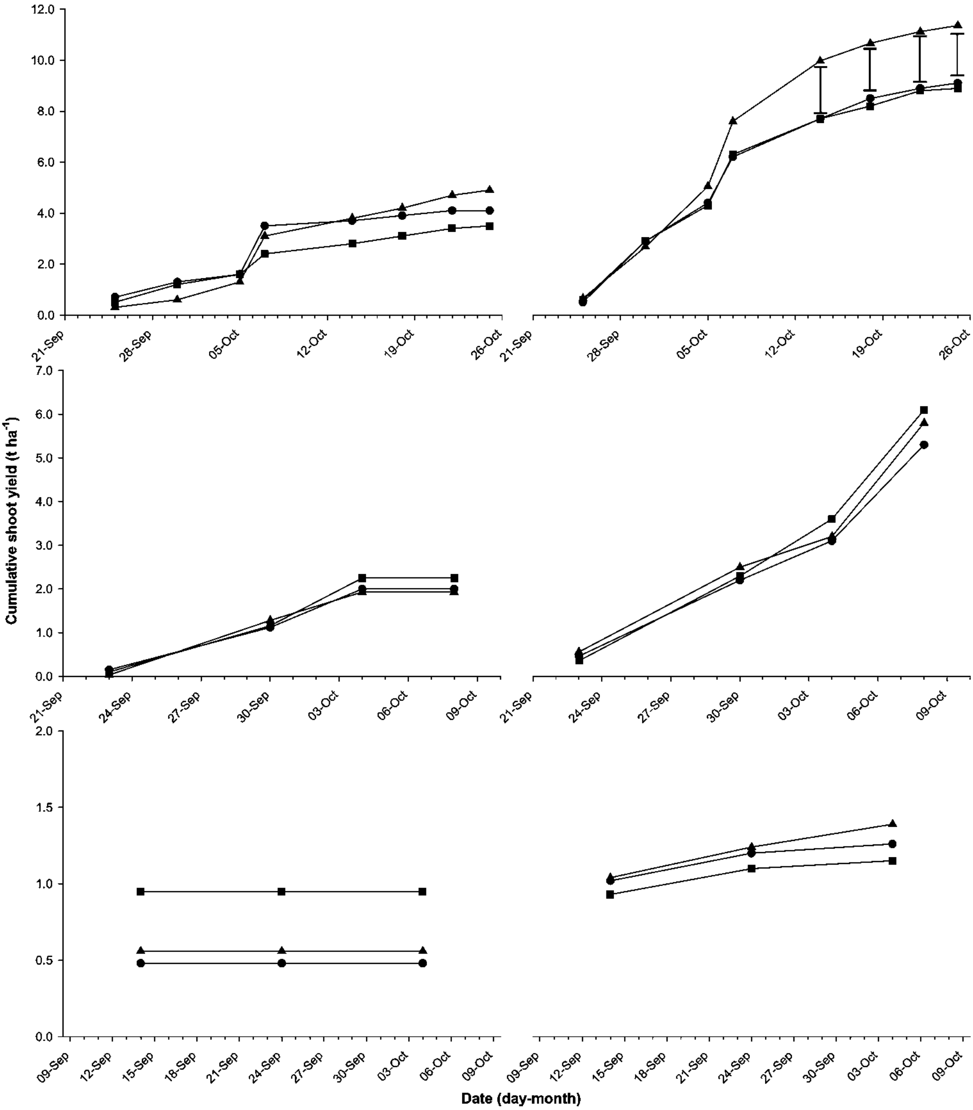

Figure 4. Effect of irrigation rate (left: 'low-irrigation' rate, right: 'high-irrigation' rate) and N application rate (■ 1.0 times the standard rate, ■● 1.5 times the standard rate, ▲ 2.0 times the standard rate) on cumulative shoot yield during (top) 1996, (middle) 1997 and (bottom) 1998. Vertical bars represent LSD.

greater number of shoots (Table 3) and not to significantly greater shoot weight (Table 4). When considering all data (Fig. 4), there was a trend that greatest yields in the high-irrigation area were achieved under the highest N application rates.

Aggregate yields steadily declined (Fig. 4) from 1996 to 1998 (from an average of approx. 6200 $kg\,ha^{-1}$ in 1996 to approx. 900 $kg\,ha^{-1}$ in 1998), an effect

Table 4.
Effect of irrigation rate (low, high) and fertilizer rate (1.0, 1.5 and 2.0 times standard rate) on mean harvested shoot weight (g per shoot) of *P. pubescens* at Belli Park from 1996 to 1998

Year	Irrigation rate											
	Low						High					
	Fertilizer rate (× standard rate)			LSD	Mean	SE	Fertilizer rate (× standard rate)			LSD	Mean	SE
	1.0	1.5	2.0				1.0	1.5	2.0			
1996	79.2	87.5	71.8	n.s.	81.0	6.58	92.1	135.9	136.0	n.s.	121.4	17.38
1997	143.5	149.9	156.2	n.s.	143.3	12.24	253.4	247.3	214.0	n.s.	238.2	51.27
1998	175.7	251.7	176.5	n.s.	197.6	16.74	259.3	239.3	286.1	n.s.	261.6	17.75

Standard rate = 250 : 50 : 141 kg ha^{-1} year^{-1} N : P : K during 1994–1996 and approx. 130 : 90 : 50 kg ha^{-1} year^{-1} N : P : K during 1997–1998. LSD = least significant difference between fertilizer rates under low and high irrigation. SE = SE of low- and high-irrigation treatments. n.s., not significant at $P = 0.05$.

that was matched (Table 3) by a decline in the number of shoots per hectare. However, average weight per shoot increased over the same period (Table 4), but not sufficiently to compensate for the loss of shoot number.

DISCUSSION AND CONCLUSIONS

Soil at the experimental site was a heavy clay with a pH of 5.1. The high bulk density of clay soils negatively affects bamboo growth. A highly significant negative relationship between soil bulk density and rhizome population density in *P. pubescens* has been reported [11]. Other studies show poorer bamboo growth at lower soil pH [12]. Thus, there was some indication that soil in our studies was sub-optimal for growth of *P. pubescens*.

The results show that growth and yield of bamboo shoots in this experiment was substantially affected by soil water availability, more so than by rates of fertilizer. Without irrigation and with only 76 and 137 mm precipitation during the shoot seasons (Sep.–Oct.) in 1994 and 1995, bamboo growth was better in the lower-lying area assigned for the low-irrigation treatment, as indicated by numbers of new shoots (Table 3). The low annual average of soil moisture tension at 60-cm soil depth showed that there was better supply of underground water (probably from the adjacent temporal pond) in that area. Water supply was apparently important during the shoot season. Although precipitation accumulated to similar amounts (800–900 mm) before the onset of the shoot season in September of each year between 1996 and 1998 (Fig. 1), different irrigation rates exhibited tremendous differences in bamboo yield in those years (Fig. 4). There was also indication that steady supply of non-excessive water volumes during the shoot season benefited bamboo production. Irrigation was more evenly distributed in 1996 than in 1997, and heavy rainfall occurred during the shoot season in 1998 (Fig. 1). Bamboo yields were much better in 1996 than in 1997 and 1998, indicating that erratic irrigation and sudden rainfall may have created short events of over-wet (i.e. most likely anaerobic) soil conditions which negatively affected bamboo shoot growth and yield.

Qiu *et al.* [8] and Biswas [7] showed how dramatically bamboo responds to increasing availability of water. Our results from 1994–1995 confirm this and suggest cultivating bamboo in a location where more water is available (e.g. near rivers) when rainfall is limited and/or seasonal, and no irrigation is available. This may be advantageous despite the danger of occurrence of temporary over-wet soil conditions. Where summer monsoonal rain occurs after the shoot season of monopodial bamboo species (as in southern Queensland, Australia), the risk of temporary over-wet conditions is minimal. The detrimental effects of the temporary over-wet conditions on bamboo growth have been reported before [13]. Our data from 1996 to 1998 show that a location with less underground water, but high irrigation (i.e. the high-irrigation area) is superior to a lower-lying area with underground water but without irrigation.

In 1994 and 1995, the years without irrigation, bamboo roots probably elongated to greater depth to take advantage of the available soil moisture in the low-irrigation area. However, in 1996 differences in leaf water potential of bamboo (Fig. 3) were only related to differences in soil water potential at 30-cm soil depth. This suggests that plant water status depended on water status of the soil A horizon. Most roots were likely located in this soil layer. This is in agreement with many studies showing that bamboo root systems are usually confined to the topmost soil layer with only a few roots extending below 40-cm depth [11, 14].

Generally, bamboo did not respond to greater fertilizer rates when soil water conditions were not optimal. Understandably, bamboo did not respond to more fertilizer in the better-drained high-irrigation area when there was only little precipitation and no irrigation in the shoot seasons of 1994 and 1995. Underground water benefited shoot production in the ‘low-irrigation’ area in those years. However, water supply was probably insufficient for optimal bamboo growth and, therefore, response to fertilizer was minimal. During the following years, occasional over-wet soil conditions such as perhaps occurred in May 1996 (Fig. 2, left) and sub optimal soil moisture due to less irrigation (e.g. when data for leaf water potential were collected in October 1996) restricted N uptake of bamboo in the low-irrigation area. Productivity and, consequently, N uptake was much greater in the high-irrigation area. N availability, however, limited bamboo growth and yield only in 1996 when better soil water conditions provided greater potential for biomass production. Leaf N concentrations reflected greater fertilizer application rates (Table 2), which were associated with greater shoot production. That there were no differences in soil N between fertilization treatments in 1996 after 3 years of imposing treatments is related to the ability of bamboo to efficiently remove inorganic N from the soil [15]. In a related study [15] we have shown that one month after applying up to 1000 $kg\,N\,ha^{-1}$ to

Bambusa oldhamii only negligible mineral nitrogen was found in the soil. Bamboo is extremely efficient in taking up mineral forms of N, making it a species highly suitable for treatment of effluent.

Tripathi and Singh [16] highlighted the efficiency of the dense root system of bamboo plants in effectively and almost immediately absorbing plant-available ions. This explains their quick response to fertilization [17] and negligible nutrient leaching in bamboo stands [18]. Application of 130, 250 and 500 kg N ha^{-1} $year^{-1}$ supported maximum shoot yields in the current experiments of 6000, 8000–9000 and 11 000–12 000 kg ha^{-1} in *P. pubescens*, revealing the great nutrient demand of bamboo but also a 'diminishing-return' relationship between nutrient application and shoot yield as previously reported [19].

The decline in shoot yield over the years when organic manure was applied in place of inorganic fertilizer (1997 and 1998) and the lesser response to fertilizer in terms of shoot yield may reflect the slower availability of the already lower application rates than in previous years. Parallel studies [15] suggest that total leaf nitrogen should not be allowed to drop below 3.0% for optimal yields, yet if leaf nitrogen was only 3.04% in the 250 kg ha^{-1} inorganic fertilizer treatment (Table 2) in 1996, it was most likely less than that, even in the '2.0 × standard organic fertilizer treatment' in later years. Unpublished data (M. Traynor, 2003) would confirm the extremely slow response of bamboo leaf N to applied organic forms of N fertilizer.

To summarise, growth and shoot yield of bamboo in our experiment depended primarily on adequate soil water conditions which predisposed plants to respond to varying levels of applied nutrients. In years when overhead irrigation was not available, underground water supply favoured growth, but when available, overhead irrigation was superior.

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