RURAL INDUSTRIES RESEARCH
& DEVELOPMENT CORPORATION

Improved Management Practices for Culinary Bamboo Shoots

Local and Export Markets

A report for the Rural Industries Research and Development Corporation

by V Kleinhenz and D J Midmore

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Management Practices for Culinary Bamboo Shoots- Local and Export Markets

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Foreword

The bamboo industry in the mid 1900s consisted of a small number of individuals dedicated to the cultivation of a number of bamboo species with the view to satisfying the local market in Australia. It is the belief of the RIRDC that complementarity must exist between those involved in new rural industries, and that RIRDC research support should be sanctioned by informal or formal industry development groups.

As no such groups existed for bamboo, one of the first milestones for this project was to establish the Australian Commercial Bamboo Corporation (ACBC) to focus on the commercial aspects of bamboo, including production, marketing and research, and the Bamboo Society of Australia (BSA), to foster interaction between members of the public, not necessarily growers, interested in bamboo from a botanical and/or gardening perspective.

The research reported on in this report, addresses key issues identified by growers at the industry meetings held at the start of the project. These include production issues covering water usage, nutrient usage and culm management and post harvest issues, focusing on the factors that can extend shelf life, including cooling, storage temperature and packaging. This report should go a long way to meeting industry demand for sound production and post-harvest management procedures.

This project was funded from RIRDC Core Funds which are provided by the Federal Government.

This report, a new addition to RIRDC's diverse range of over 800 research publications, forms part of our Asian Foods R&D program, which aims to improve profitability and promote market growth by increasing the shelf-life of fresh Asian vegetable products.

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Peter Core

Managing Director

Rural Industries Research and Development Corporation

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Contents

Executive summary

From this research project a series of practical recommendations can be made with the proviso that they should be locally tested for their relevance and validity, given that management * environment interactions are known to exist for many plant species of economic importance.

The setting up of both the Bamboo Society of Australia and the Australian Commercial Bamboo Cooperation (ACBC) has been key to the interaction between growers and others interested in bamboo. The current www site for the BSA (http://www.bamboo.org.au/) contains information on both the BSA and ACBC, and provides the relevant contacts to which to direct oneself for membership details. Both the BSA and the ACBC are vibrant, with a healthy membership; both with a regular newsletter and the latter with greater than 70 registered commercial members. These will underpin the success of bamboo as a plant species of great interest and commercial relevance.

The collation of relevant literature on bamboo shoot and timber production has led to a publication in Volume 74 of Advances in Agronomy (2001), and strengthened the position of CQU as a repository for information on bamboo. A post-doctoral fellow (funded by ACIAR) and a PhD student both work full-time on bamboo at CQU, and on an ACIAR-funded collaborative project with growers in NSW, Queensland and the Northern Territory, and with the NTDPIF and various organizations in the Philippines coordinated through the Philippines Council for Agricultural Research and Development. This is currently providing further useful information on optimum field production practices.

Our data on water use by *Bambusa oldhamii* show that higher application rates can induce earlier shoot production, but yields even on clumps of 9 years of age only reached 2.5 t ha^{-1}. These clumps had not received irrigation until the experiment began, when the clumps were 6 years old. In contrast, for *Phyllostachys pubescens*, without irrigation and only little rainfall, shoot numbers were greater with less drainage but better supply of underground water during the first 2 years of the study. With irrigation in the following years, bamboo shoot numbers and weight were much better under better-drained conditions with less supply of underground water. In those years, torrential rainfall and erratic irrigation negatively affected bamboo growth through overwet soil conditions. Shoot production was superior under better-drained soil conditions with little precipitation, and evenly distributed application of non-excessive amounts of irrigation water. Optimum soil water conditions were especially important during the shoot season and in the A soil horizon. Under those conditions, plants showed less water stress under high irrigation, and there was a significant response to application of higher rates of nitrogen.

Studies on usage by bamboo in the field focused on nitrogen (N), while a large scale pot trial allowed us to determine that bamboo supplied with N in the NH_4-N form enhanced water uptake (and by implication, growth). The rates of N:P:K extracted from nutrients applied to young bamboo plants supplied with nutrient solution was 1:0.4:1.3, notably highlighting the importance of sufficient K reserve in the field for bamboo.

But over-wet and too dry conditions limited the ability of *P. pubescens* to respond to externally added N, but under ideal soil moisture applications of 130, 250 and 500 kg N ha^{-1} $year^{-1}$ supplied yields of 6, 8-9 and 11-12 t ha-1 shoot yield. These figures will vary in other sites in accordance with the natural soil fertility and rate of soil mineralisation of N. In clumps not harvested for their shoots, higher N rates promoted the production of more, smaller diameter culms.

In order to circumvent the need to test for soil N, we developed a Diagnostic Recommendation Integrated System (DRIS) for N in bamboo. Our suggested optimum of

3.0% total leaf N represents a value above which plants only respond slightly to externally added N, while below which bamboo plants have a greater affinity for N. This value appears to be robust enough to be applicable across all the species studied, and leads to a balanced set of both number and diameter of new shoots.

Our studies on culm management focused on *B. oldhamii*, comparing constant numbers of culms of each age class (1-1-1, 2-2-2, 3-3-3 and 4-4-4 culms of 1-2-3 years of age). There was a trend that the yield of fresh edible shoots was promoted by lower standing-culm density, but yields overall were low in this experiment over the three years that it ran (it is still continuing). However, when optimising bamboo shoot and timber yield, the 3-3-3 ratio was most suitable. Older culms apparently contributed less to clump productivity (based upon data for photosynthesis), and a ratio of 4-3-2 of 1-2-3 years old culms may indeed be superior to the 3-3-3, but this remains to be proven.

The post-harvest studies concentrated on determining the relationships between shoot weight and external dimensions upon cooling (most effectively done by hydrocooling), on the contribution of cut versus remaining surface of shoots to weight loss and storage temperature (weight loss least at 1°C and greatest at 25°C) and on packaging materials (weight loss least by heat sealed PVC film or low density polyethylene (LDPE) bags). However, the latter two materials also induced most internal condensation, with a deterioration in visual quality within 14 and 21 days, respectively. Shoot respiration was, as expected, greater at 20°C than at 2°C, accounting for 18% and 34% total weight loss for shoots stored in LDPE film at 2°C and 20°C respectively, but only 4-6% of total weight loss of open-stored shoots.

Visual quality of shoots stored at 8°C declined after 6 days of storage, while that of those stored at 1°C was not notable even for one month’s storage. Based upon these experiments, the optimum packaging was at 1°C with semi-permeable materials (micro-perforated LPDE bag or LPDE film) in which shelf life could be extended beyond 28 days.

Some of the discolouration was due to the presence and growth of bacteria and fungi, for, as with other fresh vegetables, we found contamination of shoots (leaf sheaths, cut ends and internal tissue) by several species of *Bacillus,* several genera of moulds including *Fusarium,* and the presence of some coliform bacteria was also indicated.

Overall, the studies reported in this publication add to the body of knowledge upon which a successful bamboo industry will be established. Reference should be made to the outputs of a parallel project on market assessment, *Supply chain management, strategy and industry development for the commercial bamboo industry,* (RIRDC project UQ-87A, forthcoming), before prospective growers invest in the industry, for the market in Australia for fresh shoots is currently of limited size, and very small compared to the overseas export potential.

Introduction and Objectives

There is much interest in Australia in the production of fresh bamboo shoots for the local and export markets, yet individuals' efforts prior to 1997 to establish a viable industry in the past have been disjointed and ineffective.

The range of climate conditions across Australia ensure that shoot production, taking advantage of the seasonality differences between running and clumping species, can extend for close to eight months of each year.

Based upon predictions by Dooley (1992), a bamboo industry would be viable if yields of 15 t ha^{-1} or greater at farm gate prices of \$4.5 kg^{-1} or higher are obtained. More recent data (Cusack, 1999) would suggest that 10-12 t/ha would realistically result in grower profit. Data from an earlier project (RIRDC-UCQ 4A) indicate that this is a reality, with *P. pubescens* reaching these milestones six years after planting. Prices varied between \$5.50 and \$7.50 kg^{-1} throughout the 1996/1997 season (they have since been halved due to expanded supply of shoots to the market) hence it has been shown from the production point of view that the industry is economically viable. Another grower has achieved a consistent >\$10 kg^{-1} by caring for quality and sales to speciality users. All grades of fresh bamboo shoots were quickly purchased, for as with most vegetables the fresh product is preferred, even at a price differential, to the preserved product. The estimated planting of 50 ha would provide an annual gross farm-gate volume of produce between \$3.4 and \$5.2 m for the domestic market, in 1997. More recent data (Cusack, 1999) would suggest a gross income of \$2 million from 50 ha of mature plantation. Imports of canned bamboo shoots to Japan and Taiwan have exploded over the first five years in the 1990's (Vinning, 1995). Prices of fresh shoots peak (four-fold of normal price) in Taiwan in January just before Chinese New Year. Landed prices of \$4.00 kg^{-1} in Taiwan (including the 40% tariff against imported bamboo shoots) and \$4-6.00 kg^{-1} in Japan would be competitive with local production, and even desirable due to the clean/green image of produce from Australia. Additional annual income to producers is derived from the timber, which is always in demand but will require aggressive marketing to dissipate the volumes of timber anticipated in the future from current plantings.

Our earlier research has emphasised the need to manage irrigation when rainfall is insufficient to maintain optimal growth rates in bamboo. There is a paucity of information on water management for bamboo shoot production. Our own data suggests that doubling rates of irrigation prior to and during the shoot season for *P. pubescens* results in greater shoot diameter, whereas lack of irrigation in *B. oldhamii* led to fewer shoots being produced. Since shoots are initiated during the summer preceding spring shoot production, an understanding of the influence of objective temporal water supply on shoot yield (number and size – for these parameters affect quality and market price) at the time, when shoots develop, and at the time of shoot elongation, is clearly required. This should be gained in parallel with an understanding of plant water requirements to sustain total dry matter production.

Reference to culling rates of culms is more readily available in the literature (Chen, 1993; He and He, 1993) indicating that shoot number is inversely related to culm or pole number, i.e. if more shoots are left to grow on into poles fewer edible shoots can be harvested, or, expressed differently, if shoots are harvested, a greater number of shoots will be produced. An optimal culm number is probably achievable for optimal shoot production. A balance between culm or pole number (for dry matter production and timber) and shoot number (as fresh vegetable) will depend upon economic returns from both products. An understanding of the dynamics between growth of variously-aged rhizomes (Zhou et al., 1985) is important in optimising shoot yield. In monopodial bamboo, the most vigorous buds are those found in central nodes of rhizomes and those most likely to swell arise from 3- to 4 year old rhizome axes. Research on these topics is currently underway in the Peoples Republic of China.

Methods to extend storage of bamboo shoots have been trialed in Australia but so far unsuccessfully (Earthcare Enterprises trialed the vacuum packing of non-sterile and chlorox-treated shoots). However, literature exists on a plethora of topics of storage concerning bamboo shoots. Boiled bamboo shoots show microbial contamination (e.g., Nakanishi, et al., 1989). Retention of *B. oldhamii* shoots in high humidity and low temperature reduces the build up of fibre in storage (Chen et al., 1989). Peroxidase activity rapidly increased in harvested shoots (Chen et al., 1989), but no trend was noted for polyphenol oxidase. Snap freezing and preservation in oil are known to be used for bamboo shoots, and temporary storage is practiced by immersion in water. Further investigation into the literature, and discussions with colleagues at IHD (Knoxfield/CFT (Hamilton) will ensure the most suitable experimental approach to post-harvest procedures.

In essence, this research project had four separate objectives:

1. Plan and manage an industry-wide workshop with the express purpose of bringing all interested in the bamboo industry together, and to discuss and vote upon the setting up of a Bamboo Industry Council to service the needs of the industry in terms of coordination for market identification and supply of product and agreement on industry standards for fresh shoots such as size, shape, freshness and post-harvest management. Collating and translating (where necessary) information from relevant overseas reports on bamboo production and post-harvest management, and publishing in a readily accessible format.

2. Understanding of water management for bamboo.

    (a) In the field at Northern Territory and Eumundi with irrigation treatments varying in intensity and periodicity.

    (b) In the glasshouse at Rockhampton to study the influence on water requirements and contributions of variously-aged culms on shoot production.

    (c) In waste water reuse trials in comparison with other perennial species.

3. Clarification of culm-thinning and nutrient management practices suitable for clumping bamboo species.

    (a) In the field in Eumundi and in the glasshouse at Rockhampton to understand the contribution of variously-aged culms to shoot yield.

    (b) In the field at Northern Territory, Eumundi and Dayboro for data on critical nutrient concentrations.

4. Testing on-farm and under controlled conditions simple post-harvest practices following, or not, peeling of shoots. The treatments include forced air chilling or hydro cooling and assessment of relative water loss through cut or undamaged surfaces of the shoot.

Outcomes

1. Industry Cooperation

Industry cooperation began with a meeting organised by CQU. The number of participants (80) who converged on Brisbane in October in 1997 exceeded the expectations of RIRDC who part-funded and Central Queensland University (CQU) who organised the workshop. Originally planned to review the focus of a currently funded project researching production, post-harvest and marketing issues for the bamboo shoot industry, the agenda was opened up to cover basic production techniques, irrigation and fertilisation, and other issues such as propagation protocols, physiology and marketing.

Dr Jeff Davis of RIRDC opened the meeting, outlining the rationale for the use of Commonwealth funding for encouragement of new industries, especially those with recognisable financial returns for the benefit of the people of Australia. This was followed by two presentations, one each by Victor Cusack and Durnford Dart of Bamboo World and Bamboo Australia, respectively. Their talks concentrated on the pros and cons of various bamboo species suitable for shoot production, including clumping (in particular *Dendrocalamus asper*) and running (in particular *Phyllostachys pubescens*) types. While Mr Cusack explained the nature of gregarious flowering, and gave out information on establishment costs and cash flows, Mr Dart spoke of value-adding by removal of leaf sheaths from shoots and storing and transporting at 2-4°C, and marketing fresh produce from Queensland to the southern states.

With relatively high current prices for planting material, interest is keen as to the possibility of in situ propagation from mother clumps of bamboo, and Mr Jeff Barnes, of QDPI, spoke of his experience in this area. Using "canesett" application (propiconazole application at x 3 concentration recommended for sugar cane setts) to single and double node culm cuttings, and branch cuttings, the rate of success in achieving new plants was reduced compared to simply soaking in water culm. Of the six species trialled, *Gigantochloa atter* was most prolific in producing plants from culm cuttings, with 50-90% success.

Summarising three years of research by CQU on irrigation and nutrition, Dr Volker Kleinhenz highlighted the importance of access to water just prior and during the shoot season. Without sufficient water, estimated at >2000 mm per annum and concentrated just prior to and during the shooting season, bamboo cannot respond to high fertilizer rates necessary for large yields. Yields reaching 15t/ha in the sixth year after planting *P. pubescens* from seedlings and presenting a complete canopy and 1t/ha in the sixth year for *Bambusa oldhamii* with a 30% canopy, attest to the growth potential of these species in southern Queensland. Northern Territory plantations of nearly three years age are ready for experimentation on nutrition and water requirements.

Post-harvest management of bamboo can be as crucial as pre-harvest management, and Dr Peter Hoffman of QDPI drew participants attention to this. Through an understanding of the physiology of bamboo shoots, using the analogy of asparagus shoots, he highlighted the causes of product deterioration, the importance of pre-harvest management, and opportunities with modified atmosphere package and semi permeability of plastic wraps to CO_2, O_2, H_2O and C_2H_2. Participants were left in no doubt as to the importance of correct handling of the living bamboo shoots.

Another section of the program dealt with generic marketing, product promotion and benefits of associations amongst producers. Dr Peter Twyford-Jones of QDPI spoke of the need to latch onto a champion for the industry, a leader to observe, coordinate and lead, and of the commitment to adhere to a common vision within whatever association is to be formed for the bamboo industry. Opportunities for self improvement, such as with the QDPI DOOR (Do Our Own Research) approach through Participative Action Management can impact upon group synergy, and examples of other successful new industries, e.g., the lychee industry, offer models upon which to mould a bamboo association. The Northern Rivers Agricultural Development Association's President Mr Peter McLaughlin championed the need to invest time to cultivate export associations with Asians, an approach that has set his association in good stead. John Wilkie of John Wilkie and Associates emphasised the difference between marketing and selling, with the customer in the fore for successful marketing. Success depends on attention to detail in all transactions, from product volume, timing, pricing, currency of transaction, delivery system to the nicety of keeping promises along the marketing trail. The late Mr Matthew Johnson of CQU presented the concept for development of A business and marketing plan for a new product such as bamboo shoots, comparing standard, controlled and simulated test market scenarios. Such a plan was to have been developed by CQU for the bamboo industry, but funding was not forthcoming.

Before the open forum to gain consensus on programmed research, communication and the setting up of an association, or cooperative, amongst industry representatives Professor David Midmore of CQU presented a overview of the analysis of survey results received from 55 of 360 recipients across Australia. Already more than 25 ha of bamboo have been planted in Australia, with approximately one third as *P. pubescens* and one third as *B. oldhamii*. Only three producers currently market shoots and timber, and the harvest period across species spans September to May. Prices for shoots ranged from $4.00/kg for small diameter shoots to $18.00/kg for premier shoots sold directly to restaurants. The survey highlighted the lack of objective information with respect to irrigation and nutrition requirements, and the wish by respondents to access information on pricing, marketing, and export opportunities.

During the open forum the proposed continuation of research by CQU into irrigation and nutrition requirements for bamboo shoots, studies on post-harvest storage and transport protocols, and into the balance between and shoot and timber production was approved, as was the development of an industry business plan. The latter tied in with a motion from the floor to nominate a steering committee, charged with developing a draft constitution for an inclusive Australian Bamboo Association. Following synthesis of a constitution drawing on examples from other industry associations, the draft was forwarded to participants from the workshop (and others interested persons, who may care to contact the author) for feedback and voting during an inaugural meeting of the association planned for June 1998 in Brisbane. Also planned for that meeting was a session within which some of the basics of bamboo structure and physiology would be explained.

The planned meeting workshop for June 1998 was postponed to August 1998 in order that the proposed rules for the proposed Bamboo Society of Australia and the proposed memorandum and articles for the proposed Australian Commercial Bamboo Corporation be circulated as hard copy to all interested parties before the meeting.

Over one hundred enthusiasts and visionaries converged on Brisbane at the end of August 1998 to have their say in the setting up of both the Bamboo Society of Australia (BSA) and the Australian Commercial Bamboo Corporation (ACBC). The BSA was set up to promote all non-commercial aspects of bamboo interests in Australia, by way of a newsletter and annual meetings, and the ACBC to focus on the commercial aspects of bamboo including shoot and timber production, supporting research, development and marketing. Voting in of each at the inaugural meetings was unanimous.

Organised by Central Queensland University (CQU), with Rural Industries Research and Development Corporation (RIRDC) support, the one day meeting and one-day field trip provided a fine venue for formal and informal linkages between bamboo growers from Queensland, Northern Territory, New South Wales, Victoria and Western Australia. As an emerging industry, bamboo (for culinary shoots, and for timber) offers attractive financial returns to growers after the three to five year investment period. RIRDC encourages the establishment of industry corporations, preferring where possible to fund research through them than with individual growers. Following the formal voting in of the BSA and ACBC, and their respective Boards and Committees, Dr Volker Kleinhenz of CQU presented recent findings on the microbial loads and storage characteristics of bamboo shoots. Dr Jeff Barnes of QDPI (Bundaberg) followed this by providing data on success rates for vegetative propagation of bamboo while Mr Victor Cusack of Bamboo World related Thai experiences with the cultivation of *Dendrocalamus asper*, a popular culinary and timber species grown in Thailand. The first day concluded with a presentation by Mr Kevin Blackburn (NTDPIF) on the varietal comparisons and nutrition/irrigation trial set up at the Coastal Plains Research Station in the Northern Territory.

The second day attracted participants to two commercial bamboo properties north of Brisbane. At Crystal Waters, Mr Hans Erkin of Earth Care Enterprises showed his highly productive and well managed *Phyllostachys pubescens* running bamboo patch, his *Bambusa oldhamii* clumps, and his range of other special-purpose bamboo species, while at Belli Park, Mr Durnford Dart of Bamboo Australia guided visitors through plantations of the same two species plus younger groves of *Dendrocalamus latiflorus*.

Staff from CQU also organised (CQU Rockhampton, 12 December 1998), or participated in (Tatura, Victoria, 23 February 1999; Eumundi, Queensland, 14 December 1998, 24 April 1999, 30 September 1999, 7 October 2000), various Bamboo Workshops during the course of the project to provide to growers and others updated information from on-going research.

2. Information gathering

We have collected *c.* 200 abstracts of scientific articles on bamboo agronomy overseas. Most of these were not available in Australia. As an alternative to ordering those articles through Australian channels which would have cost thousands of dollars, we used our overseas contacts to collect them. This is the most significant collection of scientific literature on the subject in Australia of which a great percentage is not written in English. After sighting our collection of 'growers booklets' with help from our own Research Officers from overseas and overseas CQU students we conclude that the information contained therein is only of limited use but will nevertheless be considered for inclusion in the manuscript. This manuscript is currently with *Advances in Agronomy* with anticipated publication in June 2001. The publications will also be used extensively for publication of our research results in refereed journals.

A full list of articles published in magazines, conferences proceedings and referred journals is presented in the appendix.

3. Water usage

Most, or more likely all, of the results of experimentation with bamboo published overseas, simply estimate qualitative figures for water usage by bamboo based upon many years of experience. However, there is a more pressing requirement for quantitative information about water usage of bamboo in dry continental Australia. Commercial producers of bamboo, whether for vegetable shoots and/or timber, are seeking figures to estimate demand for irrigation but there is also interest amongst governmental agencies, environmentalists and private households to review such data for the use of bamboo in wastewater dissipation.

We, therefore, quantitatively measured water usage by young bamboo (*Bambusa oldhamii*) cultivated soilless in nutrient solution in Rockhampton. This isolation of plants into hermetically confined structures guaranteed that processes such as leaching and precipitation under field cultivation did not add errors to measurements. Due to their size, mature plants are difficult to isolate and, therefore, water demand was extrapolated using data from our own measurements and data published in overseas literature. Based upon this, optimal amounts and timing of irrigation were determined under field conditions for two bamboo species, the monopodial (‘running’) bamboo *Phyllostachys pubescens* and the sympodial (‘clumping’) *B. oldhamii* at Bamboo Australia in Belli Park near Eumundi. We also tested performance of bamboo (*B. oldhamii*) under continuous, year-round supply of wastewater in Rockhampton.

3.1 Water usage by young plants

There is no quantitative information on water usage of bamboo available in overseas literature. We, therefore, grew young (2-year-old) bamboo plants of *B. oldhamii* in 0.16 m^3 containers with sand and nutrient solution during 1998 and 1999. These isolated systems were constantly supplied with water using an automatic drip irrigation system.

While transpiration of plants generally increased during the study period studied (Figure 1) there were two peaks during the first year of investigation. Transpiration increased from September to November, decreased from November to January, increased from January to May and decreased from May to August. After August 1999, a similar pattern seemed to have commenced for the ongoing second season. It is apparent that the first peak coincided with the development of new leaves in spring. The subsequent drop in transpiration might have been due to rainfall and associated cloudiness during the mid-summer season.

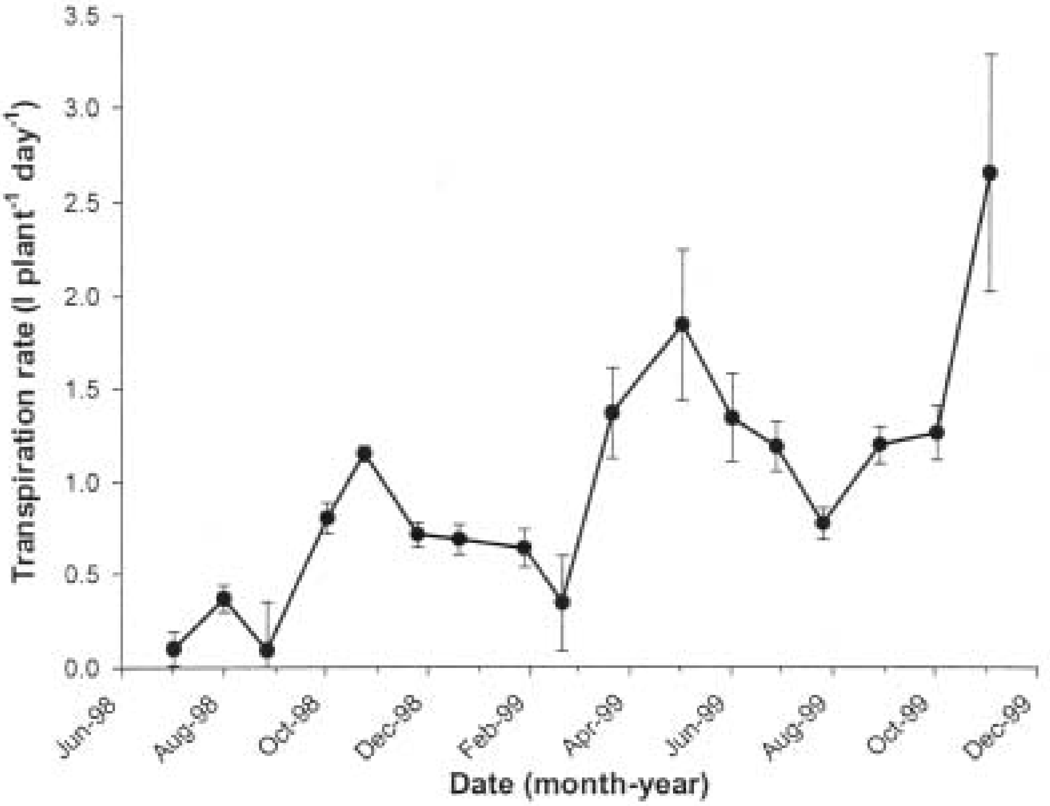

Figure 1 Transpiration in container-grown young bamboo plants (*B. oldhamii*)

3.2 Water usage by mature plants

Measuring water usage of mature bamboo quantitatively would require transplanting young plants in a big enclosure (lysimeter) and waiting several years until they reach maturity or, alternatively, uprooting mature plants and transplanting them into such an enclosure. Since both methods are beyond the means of this project, we calculated a figure using reasonable estimations from the overseas literature and from our own measurements. Water usage of plants essentially depends on their total leaf area and some authors have estimated total leaf biomass and 'specific leaf area' (ie leaf area per unit leaf biomass) for bamboo which makes it possible to calculate total leaf area. If those figures are known, water usage of bamboo can be calculated as the product of total leaf area and transpiration rate. This assumes that all green leaf is transpiring at the average measured rate. This may lead to an over-estimate of actual transpiration. We were unable to find estimates for transpiration of bamboo leaves in the literature and, therefore, measured this for a number of bamboo species currently grown in Australia. Table 1 summarises estimates and measurements on which our calculations of bamboo water usage were based and the source of these estimates/measurements.

Table 1 Estimates and measurements for calculating water usage of mature bamboo

Parameter	Value	Unit	Source
Leaf biomass (dry)	5	[t] $[ha]^{-1}$	overseas literature
Leaf dry/fresh weight	10	[%]	own measurements
Leaf biomass (fresh)	0.5	[t] $[ha]^{-1}$	own calculation
Specific leaf area	150	$[cm\ leaf\ area]^2$ $[g\ dry\ leaf]^{-1}$	overseas literature
Specific leaf area	15	$[cm\ leaf\ area]^2$ $[g\ fresh\ leaf]^{-1}$	own calculation
Leaf area index	7.5	$[m\ leaf\ area]^2$ $[m\ soil\ surface]^{-2}$	own calculation
Transpiration rate	2.3	[mmol water] $[m\ leaf\ area]^{-2}$ $[s]^{-1}$	own measurements
Transpiration rate [a]	0.04	[ml water] $[m\ leaf\ area]^{-2}$ $[s]^{-1}$	own calculation
Water usage [b]	13	[l water] $[m\ soil\ surface]^{-2}$ $[day]^{-1}$	own calculation
Water usage [c]	9	[l water] $[m\ soil\ surface]^{-2}$ $[day]^{-1}$	own estimation
Water usage	3,285	[mm water]	own calculation

[a] Atomic weight of H2O: 0.018 [g] [mmol]-1

[b] ie Water usage at maximum transpiration rate for 12 [h] $[day]^{-1}$

[c] ie Water usage at estimated average yearly transpiration rate

The estimates for leaf area were made based on a measurement for a running bamboo species (*P. pubescens*) which had 3,900 culms ha^{-1}. Clumping bamboos may have 15 culms $clump^{-1}$

planted at a density of 250 clumps ha^{-1} (= 40 m^2 clump^{-1} @ 6 m × 7 m planting distance). It follows that one mature clump may transpire (3,300 l m^{-2} × 40 m^2 =) 132,000 l water year^{-1}.

Water usage of 3,300 mm per year (last parameter in Table 1) should only be regarded as an estimate for the capacity of mature bamboo for transpiration under well-watered conditions. This figure does not imply that for optimal shoot/timber yields such quantity should be available; rather it indicates the probable maximal water dissipation rate of bamboo.

Due to water shortages under field conditions in semi-arid parts of Australia, irrigation may be feasible only prior to and during the shooting season which barely extends to a period of 6 months. Figure 2 presents the response of 4-year old (top) *B. oldhamii* and (bottom) *Dendrocalamus latiflorus* shoot yield as affected by the natural rainfall pattern during the 1998/99 season at DPIF-NT. It is clear that shoot emergence in both species coincided with peaks of rainfall. Shoot emergence and peaks of rainfall in *B. oldhamii* nearly overlapped whereas shooting in *D. latiflorus* occurred about 10 days after major rainfall events. This might be related to the greater demand for time to accumulate biomass in the relatively bigger shoots of *D. latiflorus* (Table 2).

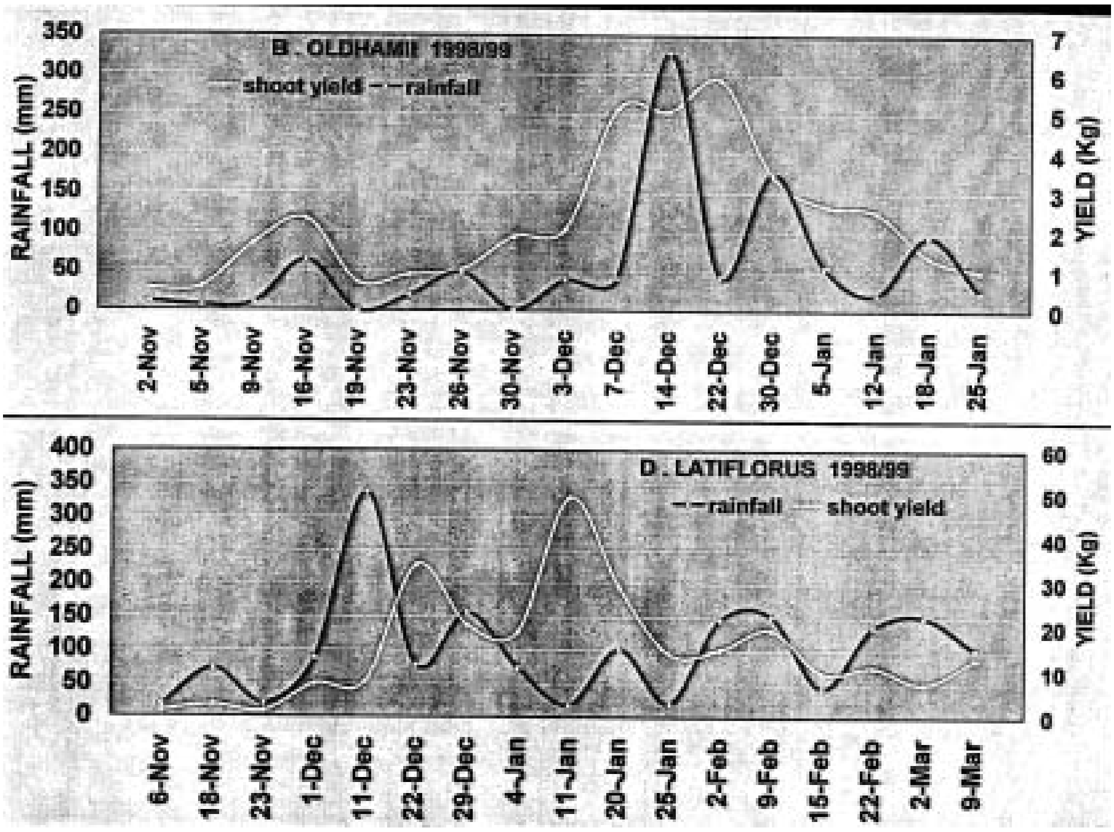

Figure 2 Shoot yield of (top) *B. oldhamii* and (bottom) *D. latiflorus* as affected by rainfall at DPIF-NT in Darwin 1998/99

Table 2 Productivity of bamboo species at DPIF-NT in Darwin, 1998/99

Species	Average shoot weight (kg shoot^{-1})	Total yield (t ha^{-1})
B. oldhamii	0.12	1.2
D. latiflorus	1.13	6.7

Planting density: 178 clumps ha^{-1}

Box 1: The trial sites and species studied.

The bamboo field trials were set up in Eumundi (SE Queensland) and Coastal Plains Research Station (Northern Territory). Two species, *Bambusa oldhamii* and *Phyllostachys pubescens*, respectively a clumping sympodial and a running monopodial were used for experimentation. Ideally, a natural summer monsoonal rainfall favours the clumping species, whereas a late winter/early spring summer rainfall favours the running species. The natural rainfall at Northern Territory suits the clumping species well, while at Eumundi, although suiting the clumping species to a lesser extent (rainfall is low at c. 1500 mm/yr – requiring supplementary rainfall during the summer) the natural rainfall does not adequately favour running species which, therefore, require late winter irrigation. At times, the limited irrigation available at Eumundi would have constrained the achievement of yield potential, particularly for the running species.

3.3 Field irrigation of bamboo

3.3.1 Phyllostachys pubescens

From 1994 through 1998, an existing stand of *P. pubescens* (planted in 1990) was split into two experimental areas to which different rates of irrigation (‘low irrigation’ and ‘high irrigation’) were applied. Both areas were fed by a main irrigation line, but the high-irrigation area had additional rotary sprinklers. Water meters indicated that approximately 50 percent more water was applied to this area. Total amounts of rainfall as measured at DPI, Nambour were almost 1,500 mm during 1994, 1995 and 1998 but less than 1,400 and 1,300 mm in 1996 and 1997 (Table 3). Figure 3 shows the distribution of rainfall and irrigation at the two different rates during 1996, 1997 and 1998.

Table 1 Total precipitation at DPI, Nambour from 1994 until 1998

Year	Total precipitation (mm)
1994	1,476
1995	1,491
1996	1,347
1997	1,240
1998	1,421

The graphs show that rainfall patterns were similar in 1996 and 1997 but in 1998 heavy rainfall occurred before and during the usual shooting season of *P. pubescens* which is from the end of September until the middle or end of October.

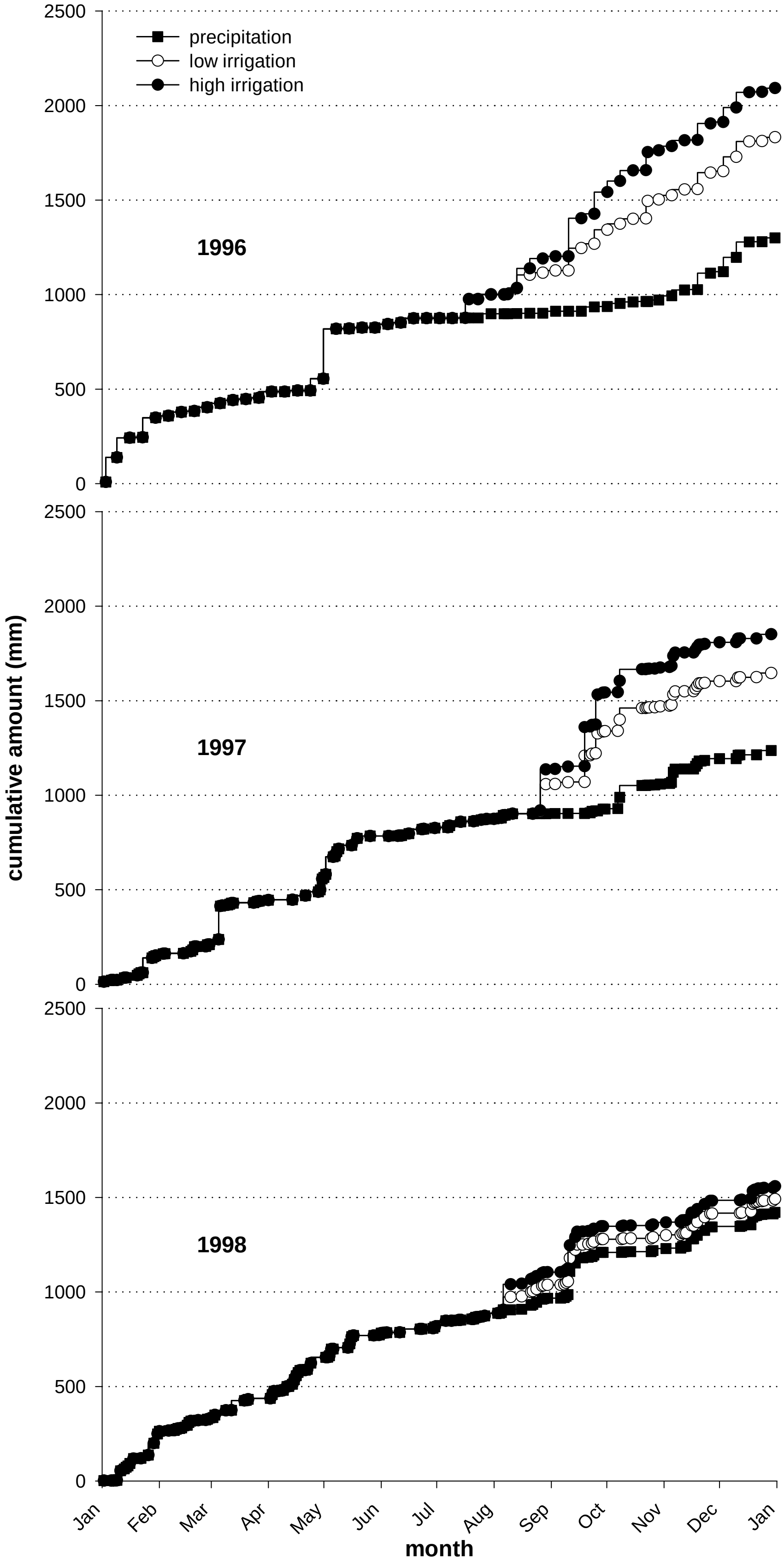

Figure 3 Cumulative amounts of precipitation and irrigation in two irrigation treatments in *P. pubescens* at Belli Park 1996-1998

During 1997, tensiometers were installed in both irrigation areas and at two depths (30 and 60 cm) with four replications and during 1998 only at 30 cm. Soil moisture tension was usually lower in the low irrigation area since this area was lower lying than the high irrigation area. In the low irrigation area (Figure 4, left) soil moisture tension at 30-cm soil depth usually exceeded soil moisture tension at 60-cm depth when soils were relatively dry (ie at high soil moisture tensions). The opposite was true in the high irrigation area: tension at 60-cm depth exceeded tension at 30-cm depth during dry periods (Figure 4, right). This shows that more underground water was present in the low irrigation area. Irrigation in the high irrigation area was effective in wetting the topmost soil layer with little effect on soil water status at 60-cm depth (eg August-September).

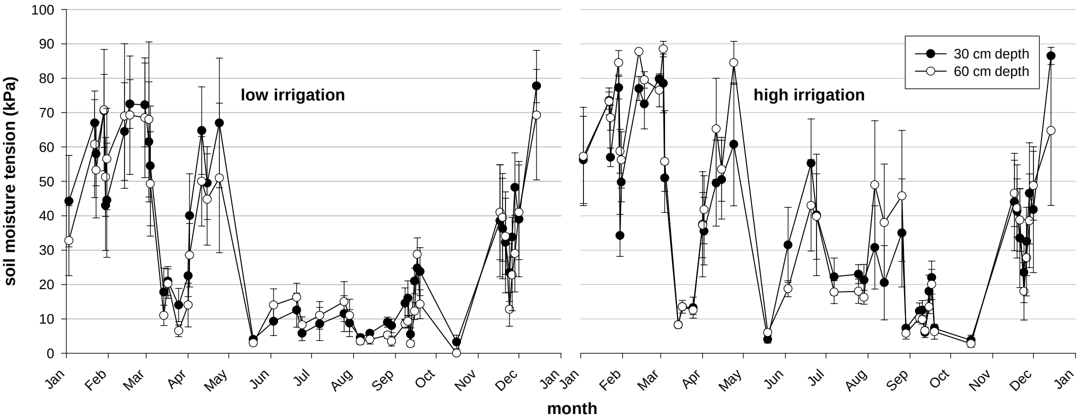

Figure 4 Soil moisture tension at 30 and 60 cm soil depth at (left) low and (right) high irrigation in *P. pubescens* at Belli Park 1997

In 1998, heavy flooding occurred in mid September. The high irrigation area provided better drainage than the low irrigation area as indicated by lower averages for soil moisture tension from August through October (Figure 5).

Data for leaf water potential were collected after a week with only 5 mm of precipitation, but 141 and 94 mm of irrigation applied in the ‘high-irrigation’ and ‘low-irrigation’ areas. Although significant only in the afternoon (1400 hours), leaf water potential was more positive in the ‘high-irrigation’ area (Figure 6). This corresponded to soil moisture tension at 30-cm depth, which was significantly more positive 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), indicating that plant water status was affected by soil water status at the shallow soil depth.

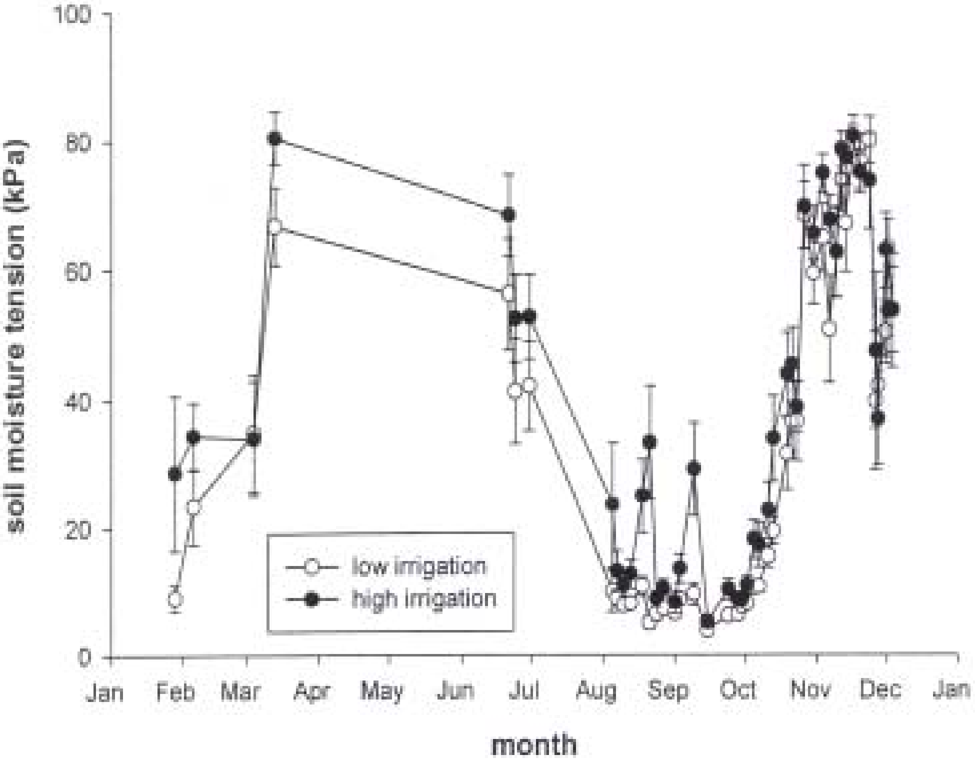

Figure 5 Soil moisture tension at 30 cm soil depth at low and high irrigation in *P. pubescens* at Belli Park 1998

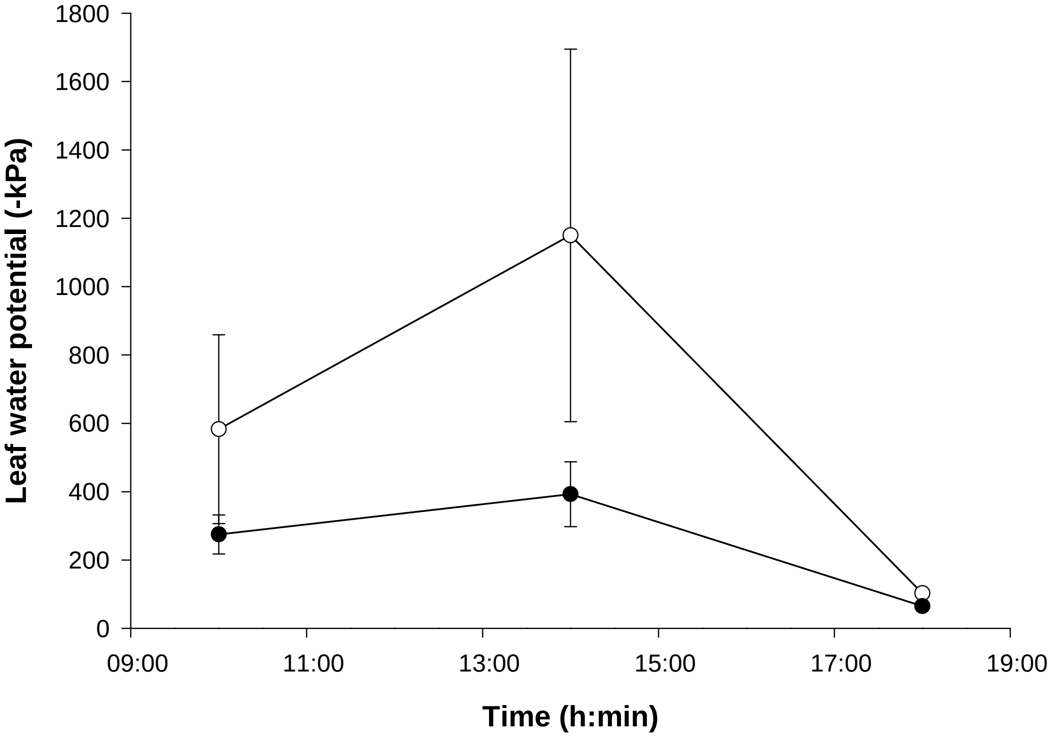

Figure 6 Leaf water potential in bamboo leaves at low and high irrigation in *P. pubescens* at Belli Park 25th October 1998

Irrigation affected the number, the diameter and the weight of annually produced fresh bamboo shoots. In both irrigation treatments, numbers of shoots increased from 1994 until 1996 and decreased until 1998. During the first two years of experimentation, more new shoots were produced when less irrigation was applied (Table 2). This effect was statistically not significant in 1994 but was in 1995. After 1995, significantly more shoots emerged in the high irrigation area.

Table 2 Effect of irrigation on total number of new shoots (# ha^{-1}) in *P. pubescens* at Belli Park 1994-1998

Year	Low irrigation		High irrigation		Comparison
	Mean	Stderr [a]	Mean	Stderr	
1994	55238	5436	45000	6220	n.s.[b]
1995	85446	11165	58333	4789	*
1996	50170	13470	89932	4915	*
1997	14120	1615	25383	2424	*
1998	3253	524	4643	563	*

[a] Standard error; b n.s.: not significant; * significant at $P = 5\%$

Diameter of new shoots was only measured in 1995 and 1996 and weight per shoot only measured during 1996-1998. During these periods, shoots from the high irrigation area were significantly bigger (Table 3) and heavier (Table 4). Cumulative yields under high irrigation, therefore, significantly exceeded those under low irrigation (Figure 7).

Table 3 Effect of irrigation on diameter of new shoots (mm) in *P. pubescens* at Belli Park 1995-1996

Year	Low irrigation		High irrigation		Comparison
	Mean	Stderr	Mean	Stderr	
1995	23.0	3.23	35.2	2.06	*
1996	47.1	2.68	52.4	1.93	*

Table 4 Effect of irrigation on individual weight (g) of new shoots in *P. pubescens* at Belli Park 1996-1998

Year	Low irrigation		High irrigation		Comparison
	Mean	Stderr	Mean	Stderr	
1996	81.0	6.58	121.4	17.38	*
1997	143.3	12.24	271.6	51.27	*

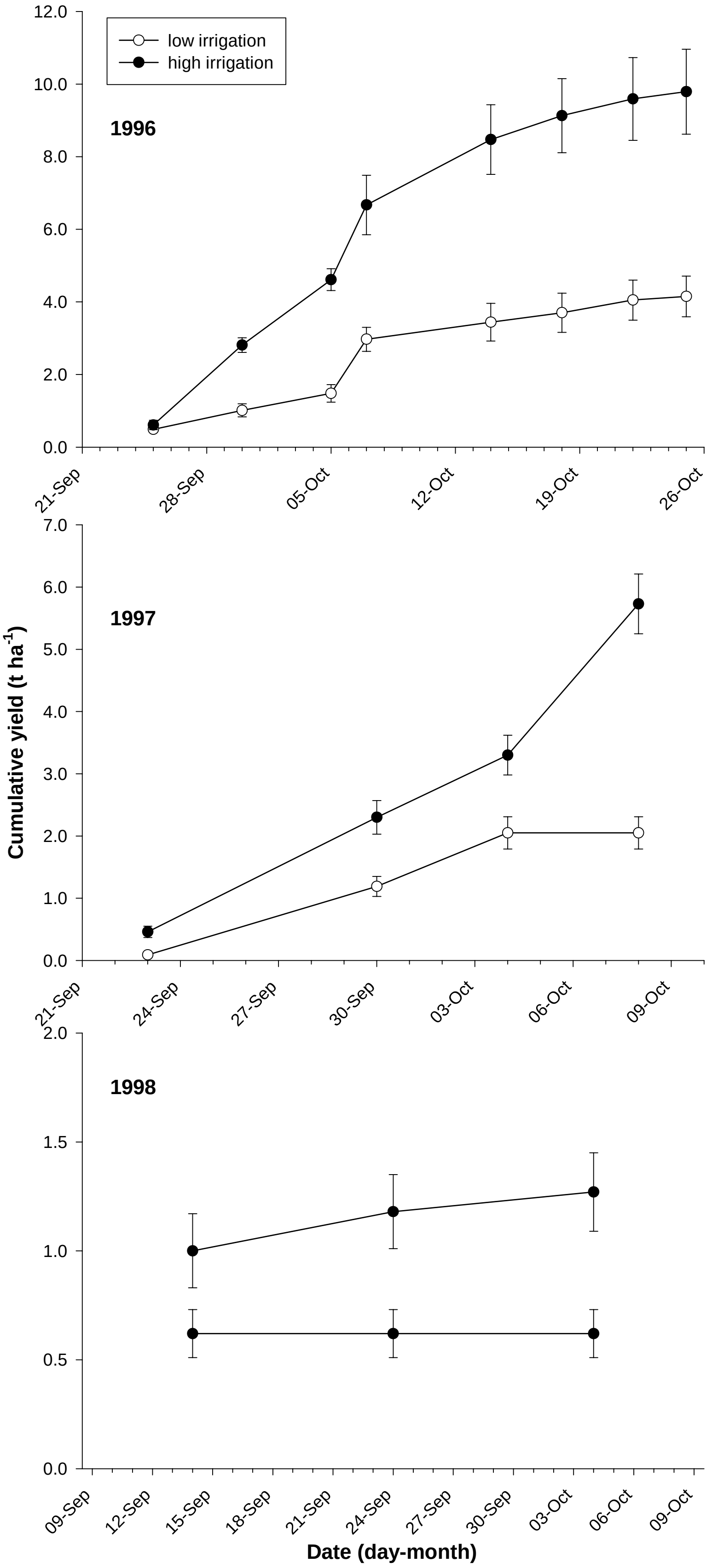

Figure 7 Effect of irrigation on cumulative yield in *P. pubescens* at Belli Park 1996-1998

Water supply and its effects on soil water conditions primarily affected bamboo growth and yield. Without irrigation and with only 76 and 137 mm precipitation during the shoot seasons (September to October) in 1994 and 1995, bamboo growth was better in the lower-lying low irrigation area as indicated by number of new shoots (Table 2). The low annual average of soil moisture tension at 60-cm soil depth showed that there was better supply of underground water in that area. This is in contrast to the heavy-rainfall conditions in May 1996 (Figure 3) when bamboo growth and yield (Table 2) were better in the higher-lying high irrigation area with less underground water and, thus, better drainage. Well-drained soil conditions in combination with high irrigation provided optimum soil water conditions for bamboo growth. This was supported by data for leaf water potential (Figure 6).

Water supply was especially 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 (Figure 3), different irrigation rates exhibited tremendous differences in bamboo yield in those years (Figure 7). 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 (Figure 3). Bamboo yields were much better in 1996 than in 1997 and 1998, indicating that erratic irrigation and sudden rainfall created short events of overwet soil conditions which negatively affected bamboo growth and yield. These data emphasise the need to ideally plant bamboo on a friable soil that is not liable to water-logging. Well balanced water supply is of foremost importance during the shooting season. It can only be speculated to what degree water supply can be reduced to an amount that guarantees transpiration and photosynthesis during the non-shooting season. However, particularly in 1996 when almost 1,000 mm of irrigation was applied, the harvest season could be extended until the end of October.

Qiu *et al*. (1992) and Biswas (1988) 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 (eg 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 overwet soil conditions. Farrelly (1984) pointed to the detrimental effects of the latter conditions on bamboo growth and our data from 1996 to 1998 shows that a location with less underground water, but good drainage (ie the high irrigation area) is superior when combined with irrigation.

In 1994 and 1995 bamboo roots probably elongated to greater depth to take advantage of the available soil moisture in the low irrigation area. However in 1998, differences in leaf water potential of bamboo (Figure 6) were only related to differences in soil water potential at 30-cm soil depth. This indicates that plant water status depended on water status of the soil A horizon. Most roots were, consequently, 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 (eg Wu, 1984 and Li *et al*., 1999).

3.3.2 Bambusa oldhamii

From 1997 through 2000, three experimental areas were superimposed onto two existing stands of *B. oldhamii* to which different rates of irrigation (‘low irrigation’, ‘medium irrigation’ and ‘high irrigation’) were applied. The ‘low irrigation’ and ‘medium irrigation’ treatments were applied onto the same bamboo stand whereas the ‘high irrigation’ treatment was applied to a separate stand. Table 5 presents average amounts of precipitation and irrigation during the shoot season of the clumping bamboo species which was between January and March of each year.

Table 5 Average precipitation, irrigation and total water supply during the shoot season (beginning of January to end of March) of *B. oldhamii* at Belli Park 1998-2000

Treatment	Precipitation (mm)	Irrigation (mm)	Total amount (mm)
'low irrigation'	441	63	504
'medium irrigation'	441	126	567
'high irrigation'	441	181	622

Although irrigation was applied at different rates and to bamboo stands at different locations, averages for soil moisture tension during 1998 were not significantly different between treatments (Table 6).

Table 6 Average soil moisture tension (kPa) at 30 cm soil depth in *B. oldhamii* at Belli Park 1998

Treatment	Mean	Stderr
'low irrigation'	-53.4 a [x]	7.0
'medium irrigation'	-53.2 a	6.9
'high irrigation'	-40.0 a	11.7

[x] Numbers followed by the same character are not significantly different (*P* = 0.05)

In contrast to the cumulative effect of higher irrigation on yields in *P. pubescens*, total cumulative yields in *B. oldhamii* were only significantly improved by greater volumes of irrigation water in 1998 (Figure 8). However, higher irrigation promoted later yields in 1998 and highest irrigation promoted earlier yields in 1999 and 2000. This could be attributed to distribution of rainfall which was higher in the early shoot season in 1998 but higher in the late shoot season in 1999 and 2000 (data not shown). Shoot weight was not significantly affected by irrigation within years but greater increases in weights between years were observed with higher irrigation (Table 7).

Table 7 Average shoot weight (kg ± stderr) of *B. oldhamii* at Belli Park 1998-2000

Treatment	1998	1999	2000
'low irrigation'	0.53 ± 0.036 a[x]	0.40 ± 0.016 a	0.55 ± 0.035 a
'medium irrigation'	0.56 ± 0.049 a	0.49 ± 0.068 a	0.59 ± 0.058 a
'high irrigation'	0.53 ± 0.035 a	0.44 ± 0.022 a	0.62 ± 0.019 a

[x] Numbers followed by the same character are not significantly different (*P* = 0.05)

Yields in *B. oldhamii* increased from circa 1 t/ha in 1998 to almost 2.5 t/ha in 2000, indicating that plants had not reached maturity and, consequently, their full yield potential. In contrast to plants of *P. pubescens* which had attained their yield potential, extra supply of irrigation water to *B. oldhamii* was apparently not as effective. The overall difference between irrigation treatments for *B. oldhamii* was only 120 mm (504-622 mm), due to drought-induced lack of irrigation water. Greater differences between treatments, and greater overall yields would likely have been recorded if irrigation had supplied 500, 1000 and 1500 mm in the low, medium and high treatments.

Box 2: Irrigation and water usage

Under well-watered conditions, our data suggest that bamboo could use an estimated 3300 mm/yr rainfall equivalent – an indication of the probable maximum water dissipation rate for bamboo rather than the optimal water requirement for bamboo. In reality, the requirement is probably somewhat less. For *P. pubescens* (a running bamboo), supplementary irrigation of 500-800 mm during August-October in Eumundi increased two to three fold the yield of shoots over the three years studied, illustrating the non-suitability of the natural rainfall to sustain optimum yield in this environment. The major effect of the additional irrigation was to increase individual shoot size. Well-drained soil conditions, with high yet steady irrigation rate provided optimum soil water conditions for *P. pubescens*.

Trials on a stand of *B. oldhamii*, which had not received supplementary irrigation until they were 6 years of age, only showed a response to supplementary irrigation in one of the three years of experimentation. On average, only between 60 and 180 mm/yr was applied as supplementary irrigation (due to the prevailing drought conditions over those years, and most stored water having been earlier used for *P. pubescens*) therefore, it was not surprising that yield benefit were minimal.

The data from Northern Territory show the close association between timing of precipitation and shoot production in *B. oldhamii* and *D. latiflorus* and the data from Eumundi suggest that water just prior and in the shoot season should reach 1000 mm for high shoot yields to be obtained.

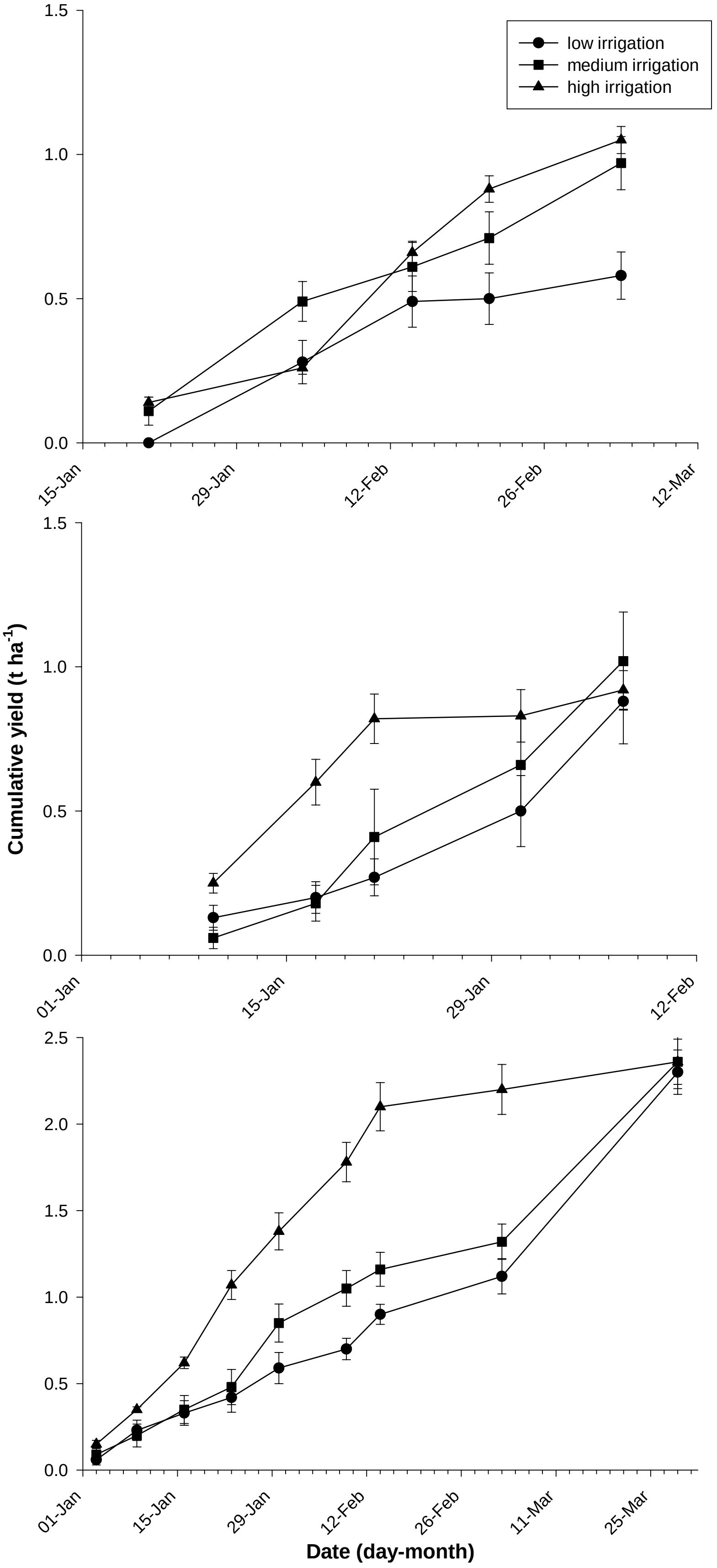

Figure 8 Effect of irrigation on cumulative yield in *B. oldhamii* at Belli Park

1998-2000

3.4 Usage of wastewater

In 1998, bamboo (*B. oldhamii*) was introduced to an experimental wastewater treatment site at SW Kele & Co. Pty Ltd in Rockhampton (Figure 9). Wastewater is pumped into a holding tank and consists of two fractions: (1) treated workshop wastewater (treated graywater) and (2) household wastewater (blackwater).

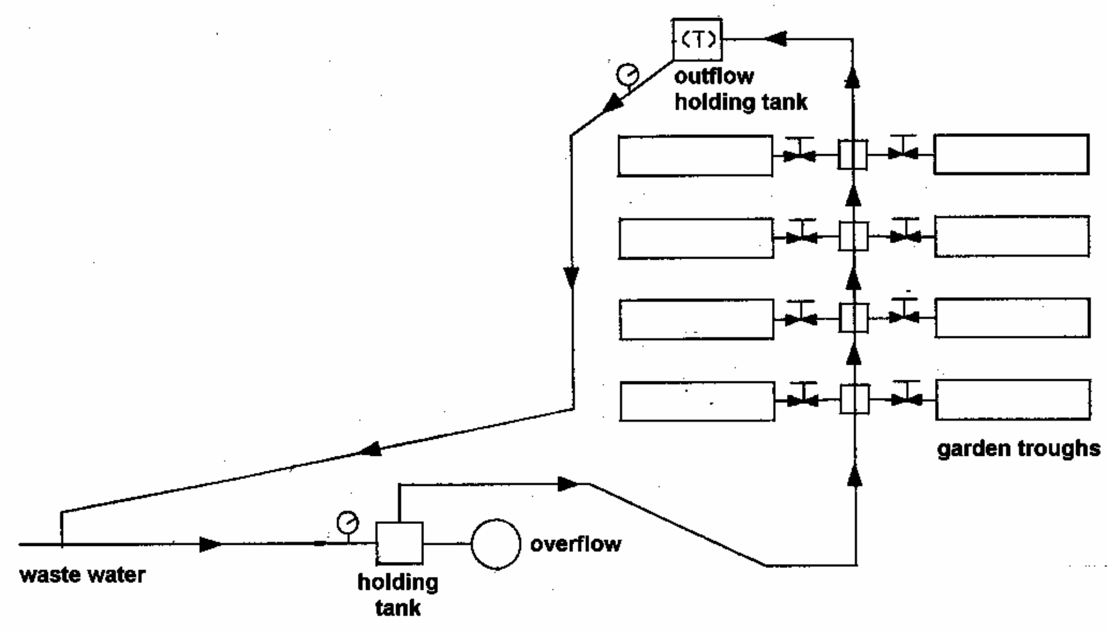

Figure 9 Wastewater treatment system installed in 1998 at S W Kele & Co. Pty Ltd, Rockhampton

Graywater is untreated wastewater from the wash up area for the workers at the company. It contains high amounts of oil, grease, soaps, and human sweat and dead skin. This water is directed to a grease trap. The water is allowed to pass through a vertical grease trap until the majority of the oil and grease has been removed. This treated graywater still smells of soap; the grease trap's effectiveness in removing soaps is unknown. Blackwater is the sewage water of a standard household after it has passed through, and has been treated in, a septic tank. This water is anaerobic and high in nutrients, such as nitrate and ammonia. It is also high in faecal coliform bacteria with measurements normally in the range of $10^5 – 10^7$ organisms per 100 ml. At present the treated graywater has approximately four times the volume of the blackwater and about 400 litres of this mixture is produced daily and pumped into the system.

A mixture of treated graywater and blackwater is pumped out to the underground garden troughs. The wastewater flows into the bottom of garden troughs into a layer of gravel on top of a punched plastic film. The plastic film allows water to penetrate but essentially prevents movement of the garden soil in the upper part of the trough into the gravel. Plants root in the garden soil which is covered by another plastic film. This film is cut lengthwise to allow new bamboo shoots to emerge, but prevents rainwater entry to the system. After passing through the system of garden troughs, excessive water is collected in an outflow holding tank and pumped back to the inflow.

During the first season of *B. oldhamii* grown with wastewater, there were two periods of shoot growth, the first one from September 1998 to January 1999 and the second from January until June 1999 (Figure 9a).

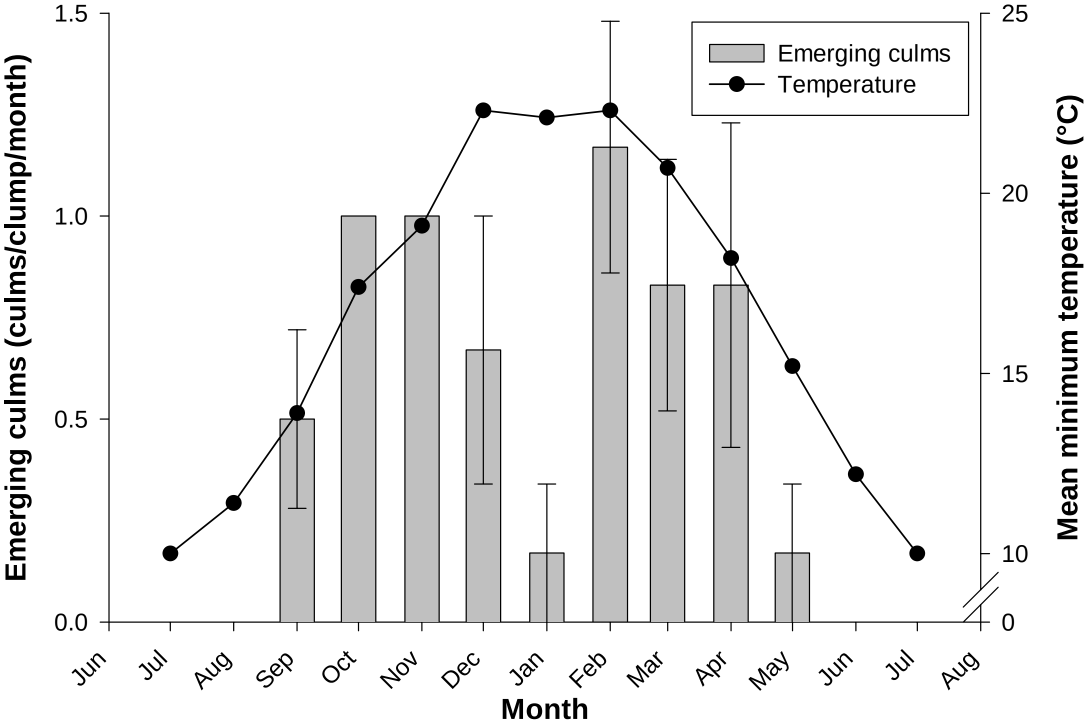

Figure 9a Number of emerging new culms (mean ± stderr) of *B. oldhamii* in the wastewater treatment experiment at SW Kele & Co. Pty Ltd and mean monthly minimum temperature in Rockhampton (1998/9)

Data from the second season (1999/2000, not shown) confirmed that when the growth factor water is available in virtually unlimited amounts such as in this system, only low temperatures limit year-round growth and shoot production. It would be interesting to determine whether under conditions of permanent high temperatures such as in the tropical parts of Australia (eg the Northern Territory), effective irrigation systems could provide year-round production of edible bamboo shoots.

4. Nutrient usage

Nutrient availability is usually the most important soil chemical property governing bamboo growth and yield. The contents of available nutrients in the soil are positively related to yield and explain much of the variation in yield across bamboo-growing sites and regions (eg in China; He and Ye, 1987; Hong, 1994). Nutrient availability can be managed comparably easily through fertilisation.

4.1 Nutrient usage by young plants

As outlined in section 3.1, we grew young bamboo plants (*B. oldhamii*) in containers during 1998 and 1999. Field-based fertilisation experiments may not reflect actual nutrient absorption rates due to the complicated interactions of nutrients after their application in soil but in isolated systems which are constantly supplied with nutrients, these interactions can be eliminated. During 1998, different forms of nitrogen (ammonium, nitrate and ammonium nitrate) were applied to study preference of bamboo for nitrogen forms and effect of nitrogen form on water usage and absorption of other major nutrients (ie phosphorus and potassium) by bamboo.

The form of nitrogen applied had a significant effect on water usage of bamboo. Understandably, application of any form of nitrogen accelerated water usage of bamboo (Figure 10). However, plants absorbed more water when only NH_4-N was applied. This might be explained by the preference of plants to the molecular state of nitrogen: in contrast to dicotyledonous plants, graminaceous plants have comparably low values of ion-exchange capacity and are, therefore, more effective in absorbing monovalent cations (NH_4^+) than divalent cations (NO_3^{2+}). This is known for grasses such as rice but has never been shown for bamboo.

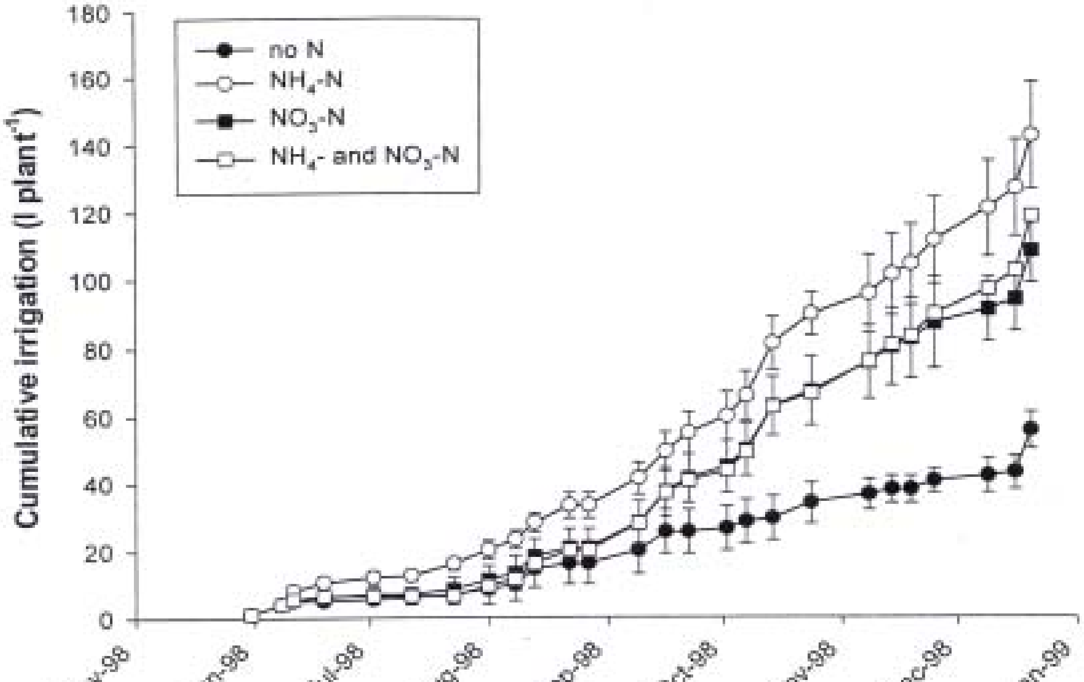

Figure 10 Effect of N-form on water usage of bamboo (*B. oldhamii*) in Rockhampton

In many overseas field-based experiments, the optimum ratio between N, P and K for fertilisation purposes was determined. Results from such trials depend on soil parameters and particularly the nutrient-supplying capacity of soils. A much more limited number of studies has covered results of nutrient analysis in different plant parts of bamboo and these studies generally agree in that K is the nutrient most significant to bamboo growth, followed by N and to a much lesser degree P. In our direct measurements of absorption of these major nutrients by bamboo, this was confirmed (Figure 11). The N:P:K ratio between absorbed ions was 1.0:0.4:1.3 after 16 months of cultivation in nutrient solution.

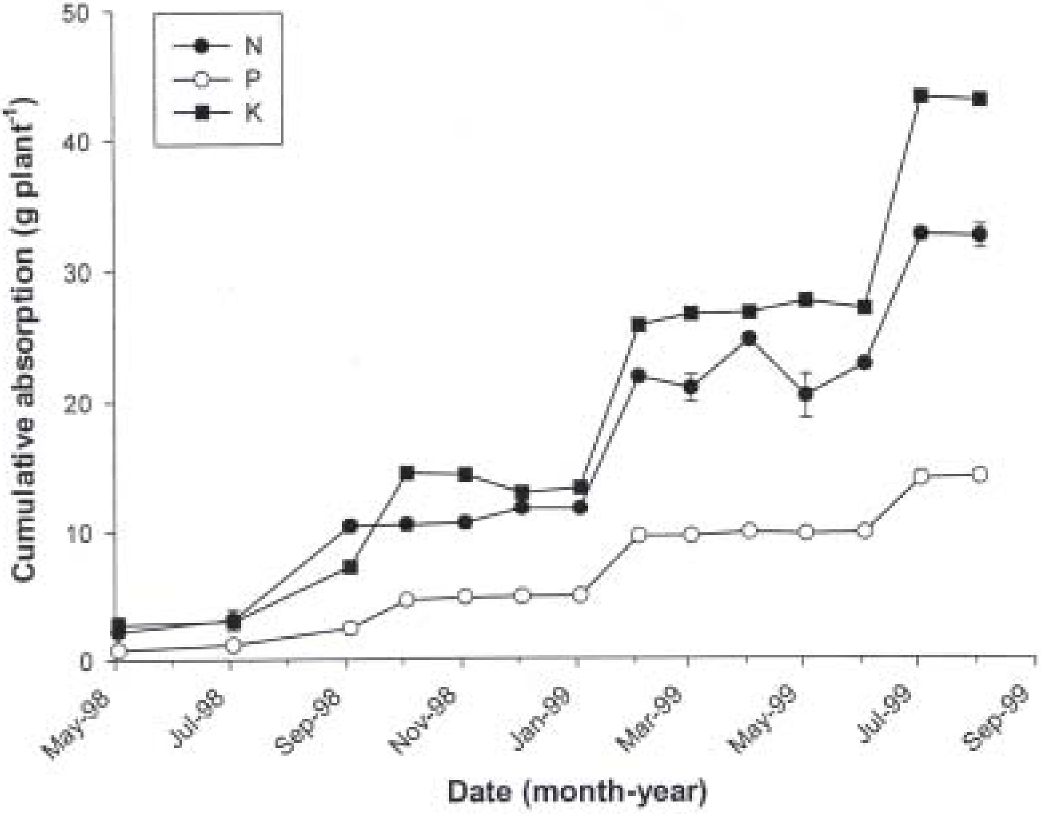

Figure 11 Absorption of N, P and K by bamboo (*B. oldhamii*) in Rockhampton

4.2 Nutrient usage of *Phyllostachys pubescens*

From 1994 through 1998, three fertiliser treatments: (1) a ‘standard’ rate, (2) 1.5 times the ‘standard’ rate and (3) 2.0 times the ‘standard’ rate were applied to an existing stand of *P. pubescens* which was irrigated with two different rates (section 1.3.1). Individual irrigation areas were split into four replicate rows, with three plots along each row randomly assigned one of the fertiliser treatments. From 1994 through 1996, inorganic fertiliser was applied at a (‘standard’) rate of 250:50:141 kg ha^{-1} $year^{-1}$ N:P:K and during 1997 and 1998 composted chicken manure (approximately 130:90:50 kg/ha/year N:P:K) was used. Fertiliser was applied in July before the shoot season.

After three years of N application, soil N was not significantly different between N application rates (Table 8). In contrast, leaf N increased significantly with higher N rates. All leaf N concentrations were much greater compared with a nearby non-fertilised bamboo stand (1.70 ± 0.054% N).

Table 8 Effect of fertiliser rate on total soil N (0-30 cm soil depth) and leaf N in *P. pubescens* at Belli Park in 1996

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

[x] Numbers followed by the same character are not significantly different ($P = 0.05$)

N 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 x standard treatment rate (Table 9). There was no significant effect of N application rates on weight of shoots (Table 10).

Table 9 Effect of irrigation and fertiliser rate on total number of new shoots (shoots/ha) of *P. pubescens* at Belli Park 1994-1998

Year	Irrigation rate							
	Low				High			
	Fertilizer rate			LSD [x]	Fertilizer rate			LSD
	1.0 ×	1.5 ×	2.0 ×		1.0 ×	1.5 ×	2.0 ×	
1994	60000	43929	31429	n.s.	50714	65714	49286	n.s.
1995	97143	100000	76071	n.s.	50714	68571	55714	n.s.
1996	43724	47041	59745	n.s.	90102	75204	104490	20468 *
1997	13878	15153	13214	n.s.	20867	27474	27806	n.s.
1998	2857	3827	3469	n.s.	4796	4541	4592	n.s.

[x] Least significant difference

Table 10 Effect of irrigation and fertiliser rate on harvested individual shoot weight (g) of *P. pubescens* at Belli Park 1994-1998

Year	Irrigation rate							
	Low				High			
	Fertilizer rate			LSD	Fertilizer rate			LSD
	1.0 ×	1.5 ×	2.0 ×		1.0 ×	1.5 ×	2.0 ×	
1996	79.2	87.5	71.8	n.s.	92.1	135.9	136.0	n.s.
1997	143.5	149.9	156.2	n.s.	253.4	347.3	214.0	n.s.
1998	175.7	251.7	176.5	n.s.	259.3	239.3	286.1	n.s.

Figure 12 presents cumulative shoot yields in the two irrigation areas from 1996 to 1998. These data reflected data for number of shoots (Table 9): higher fertiliser application improved shoot yields only in 1996 in the ‘high irrigation’ area. Since the latter was due to a significantly greater number of shoots (Table 9) and not to significantly greater shoot weight (Table 10), it could be concluded that nitrogen improved yield due to the effect on number of shoots rather than their weight. When considering all data, there was only a trend that greatest yields in the ‘high irrigation’ area were achieved under the highest N application rates.

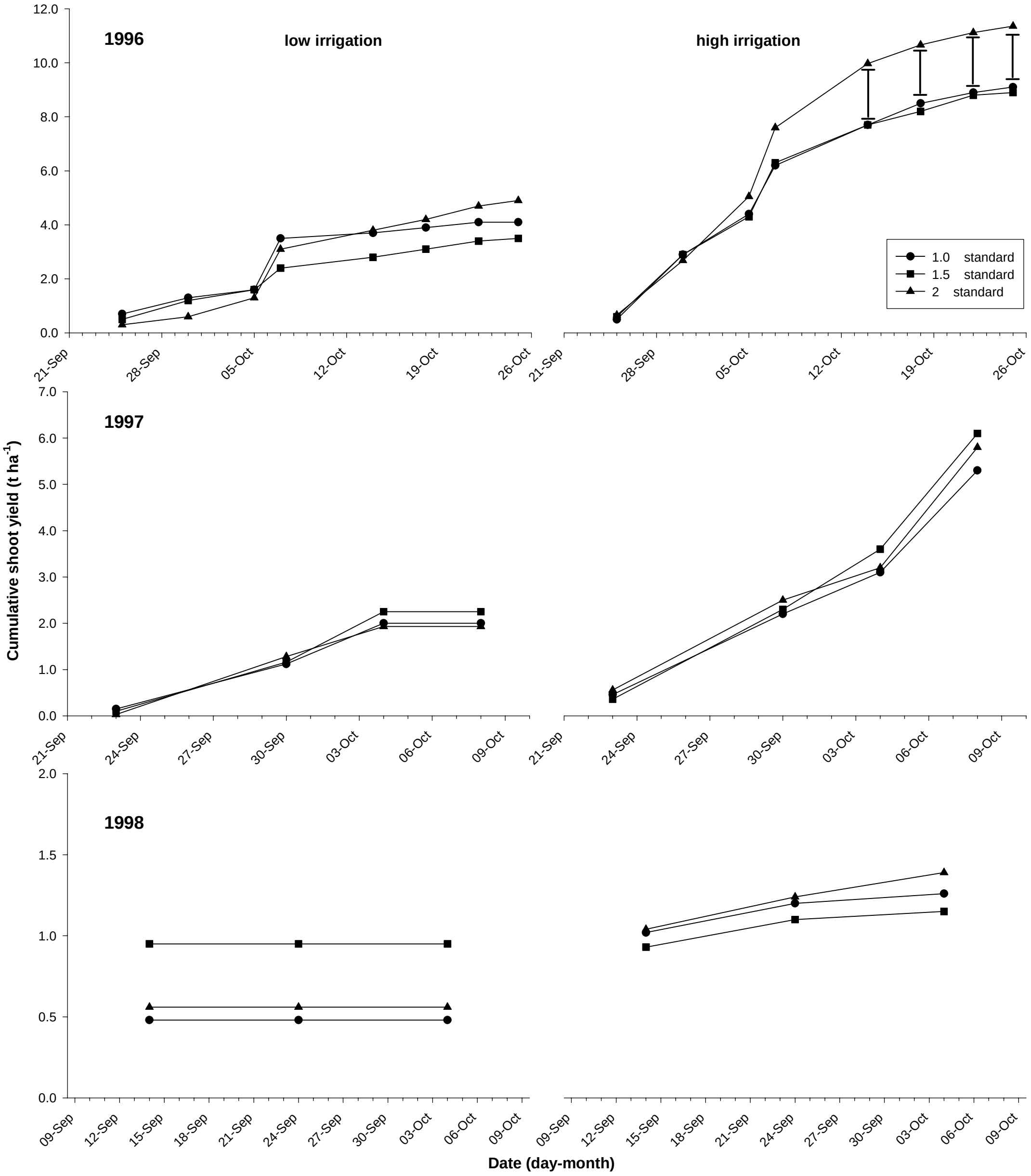

Figure 12 Effect of irrigation and fertiliser rate on cumulative shoot yield of ***P. pubescens*** **at Belli Park 1996-1998. Vertical bars represent LSD.**

Plant growth generally follows a ‘minimum factor’ concept, ie there will be no response to growth factors other than the growth factor which restricts growth most significantly. Bamboo did not respond to greater N rates when soil water conditions were not optimal. Therefore, bamboo did not respond to more N in the better-drained ‘high irrigation’ area when there was only little precipitation and no irrigation in 1994 and 1995. Underground water was beneficial for shoot production in the ‘low irrigation’ area in those years. However, water supply was probably insufficient for optimal bamboo growth and, therefore, response to N. During the following years, occasional overwet soil conditions and suboptimal soil moisture due to less irrigation restricted N uptake of bamboo in the ‘low irrigation’ area. Productivity and, consequently, N uptake was much greater in the ‘high-irrigation’ area. Nutrient 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 N application rates (Table 8), which were associated with greater shoot production. Nitrogen, which was not absorbed by bamboo, was probably leached; hence, there were no differences in soil N between fertilization treatments after 3 years of imposing treatments. It can be concluded that fertilisation can only improve bamboo growth if soil water conditions are well managed. Application of 130, 250, and 500 kg ha^{-1} year^{-1} N supported annual shoot yields of 6, 8-9, and 11-12 t ha^{-1} in *P. pubescens*, revealing the great nutrient demand of bamboo but also a ‘diminishing-return’ relationship between nutrient application and shoot yield.

4.3 Diagnosis Recommendation Integrated System (DRIS) for N

Effects of nutrient application on response in bamboo depend on a large number of factors including soil-related factors (eg adsorption and absorption capacities, nutrient-supplying power and soil water relations), plant-related factors (eg species) and numerous other environmental factors (eg temperature). There can be little doubt that analyses of plant tissues are a much better indicator of the nutrient status of crops than are soil analyses. Response of crops to available nutrients in the growth media usually follows a hyperbolic relationship with great yield response to nutrient application at low plant nutrient levels and a decreasing rate of response with increasing plant nutrient contents (the ‘Michaelis-Menten’ relationship). This theory has been applied to nutrient relationships in many crops and is valid for most plant nutrients. Therefore, tissue analyses have been adopted to guide fertilisation in many important annual and perennial crops. The last fully expanded leaf is often used as an index tissue since this plant part is usually the best indicator of the current nutrient status of the plant during its active growth phase. This method can be used across bamboo species and cultivation sites free of extreme conditions (eg drought or waterlogging). If fertilisation is to be based on plant analysis, there must be calibration of application rates to plant response. To calibrate this curve for specific site conditions, response of bamboo to varying nutrient application rates should be measured on individual sites to define response curves locally. This approach has been named ‘Diagnosis Recommendation Integrated System’ (DRIS) and is the basis for fertilisation in many important plantation crops such as oil palm, coffee and cocoa but also annual crops such as vegetables. For those crops, relationships and cross-relationships between macronutrients and even micronutrients have been studied to guide fertilisation. As a first attempt to develop a DRIS for bamboo, we developed a system (a response curve between leaf nitrogen and application rate of fertiliser N) for the element ‘nitrogen’ which is the second-most significant nutrient for growth of bamboo.

In the first experiment, four rates of inorganic nitrogen (250, 500, 750 and 1000 kg N ha^{-1} as urea) were applied to single clumps of *B. oldhamii* in February of 1998. Soil nitrogen analyses proved to be ineffective in showing differences between treatments, eg one month after application of fertiliser, only 0, 0, 35 and 7 ppm of available N could be found in the soil for application rates of 250, 500, 750 and 1000 kg N ha^{-1}, respectively. This indicates that either the root system of bamboo is very effective in absorbing available soil nitrogen, or less likely that leaching and/or immobilisation removed N not used by bamboo. Analyses of total N in the last fully expanded leaves revealed differences between fertiliser treatments and are, therefore, effective measures of the nutritional status of plants. Concentrations of leaf N increased with increasing N application rates (Figure 13). Differences between 500, 750 and 1000 kg N ha^{-1} were small, but leaf N was lower when only 250 kg N ha^{-1} were applied. Leaf N decreased with time after application of fertilisers.

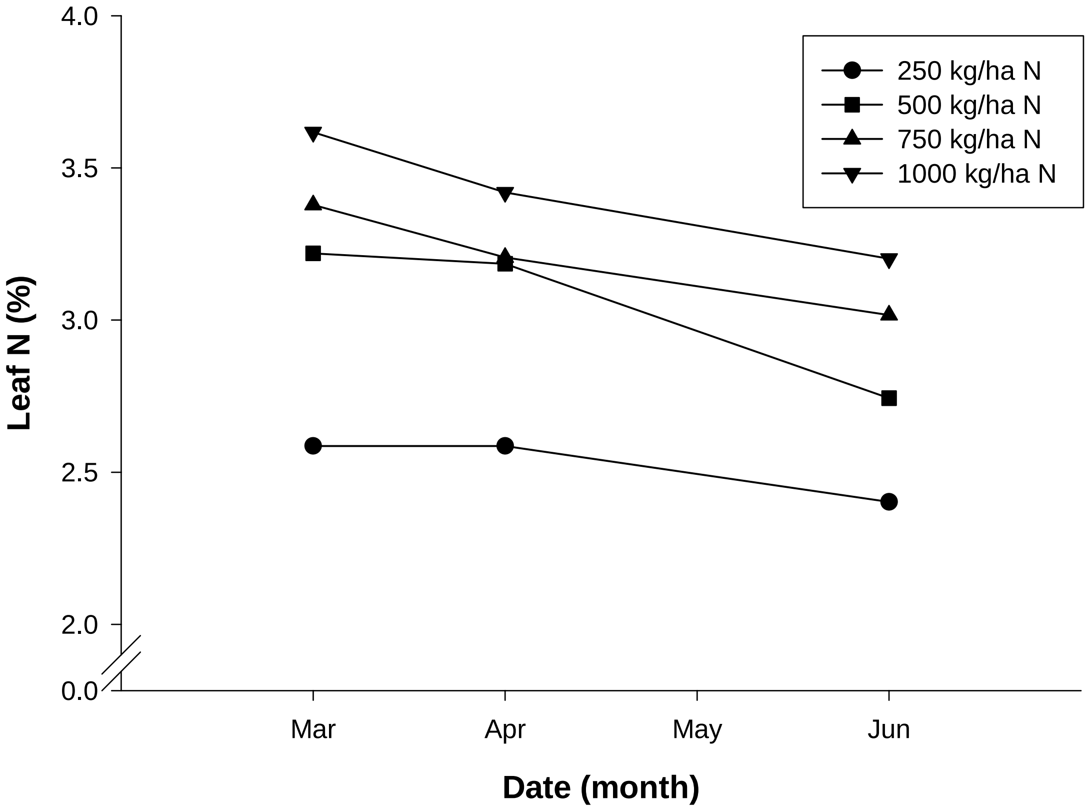

Figure 13 Effect of N application rate on leaf N concentration in *B. oldhamii* at Belli Park

Before transplanting *B. oldhamii* to the wastewater treatment facility (section 3.4), leaf N concentration was below 1.5 percent but increased to about 3.5 percent within three months. Concentrations of nutrients in the growth medium were excessive since not all nutrients were absorbed. Therefore, N concentrations around 3.5 percent would indicate the likely 'maximum' concentration of leaf N in *B.oldhamii*. In fact, the highest N concentration that we have ever measured in this species was 3.617 percent, after application of 1,000 kg ha^{-1} N to a clump of *B. oldhamii* (Figure 13).

In a similar experiment to the abovementioned with *B. oldhamii*, we applied 300 kg ha^{-1} N to a stand of *P. pubescens* at Dayboro. There was a quick and significant response compared to the control one month after N application (Figure 14). Leaf N reached a maximum after two months and was lower thereafter. Rapid absorption of N was associated with increased photosynthesis and, therefore, biomass accumulation as indicated by leaf C concentrations (Figure 15). Leaf C increased in the fertilised plots whereas C in the unfertilised plots decreased.

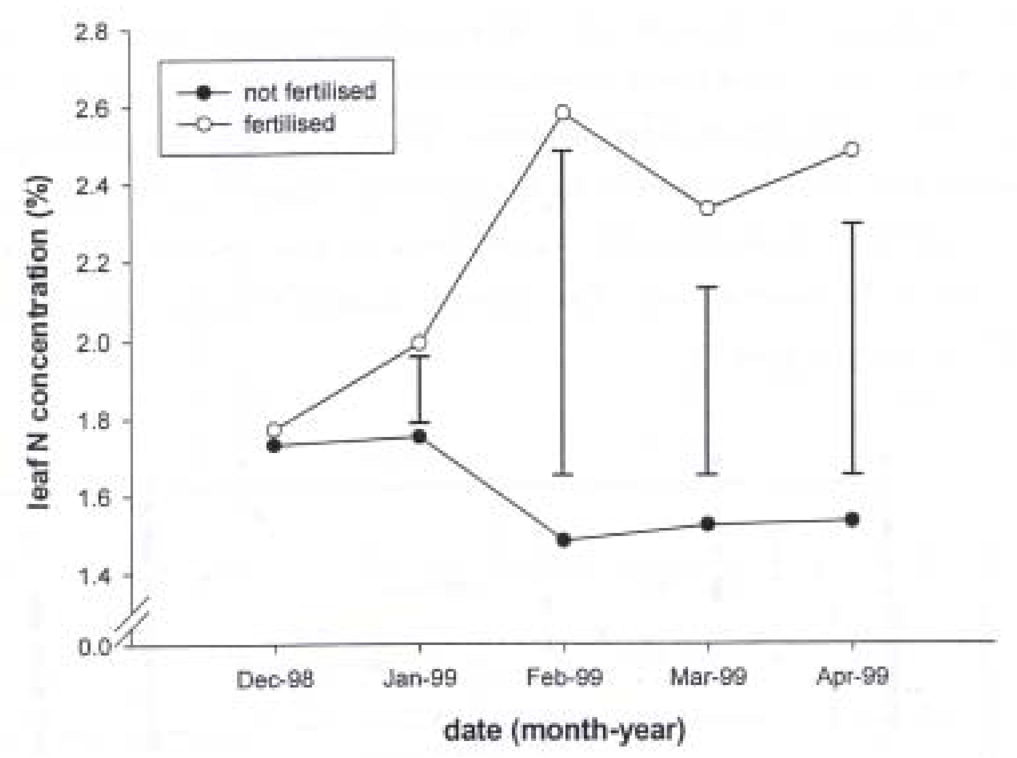

Figure 14 Leaf N concentration as affected by fertilisation (300 kg ha-1 N) in *P. pubescens* at Dayboro (bars represent LSD at 5%)

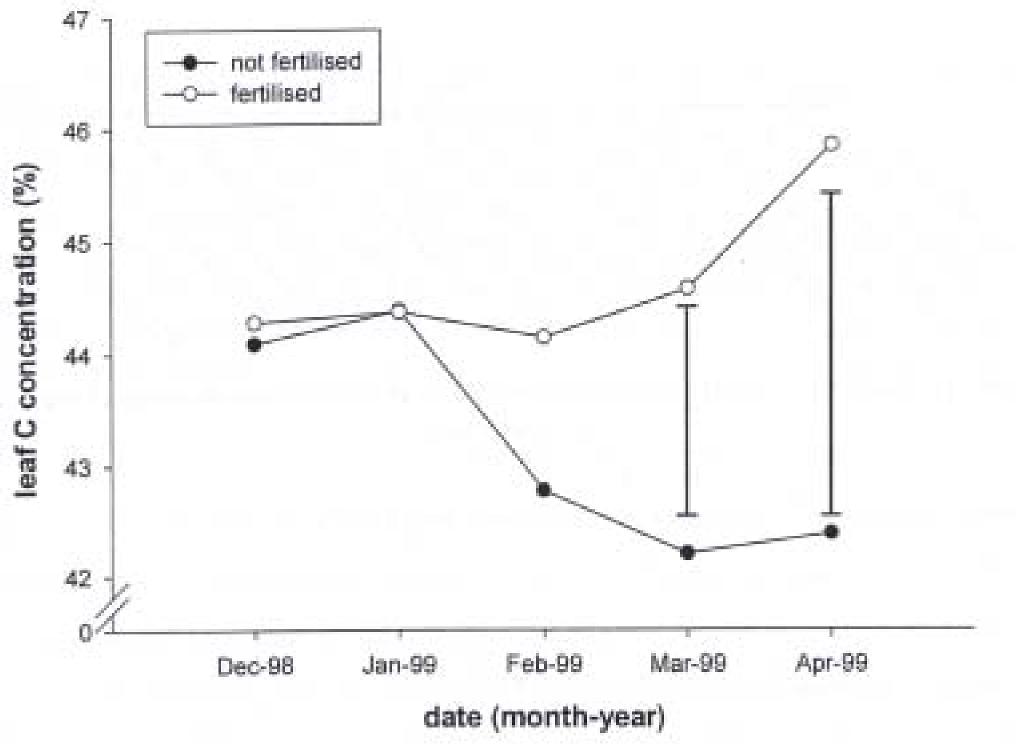

Figure 15 Leaf C concentration as affected by fertilisation (300 kg ha^{-1} N) in *P. pubescens* at Dayboro (bars represent LSD at 5%)

Figure 16 presents a summary of leaf-N data of different bamboo species at different locations in Australia. We roughly estimated a ‘lower limit’ for leaf N at about 2.0% N since the colour of leaves of several bamboo species at or below this level appeared yellow to light green. N concentrations at or above the ‘upper limit’ of 3.5% N were only measured when nutrient supply was excessive, eg after application of ≥ 500 kg ha^{-1} N and in the wastewater trial. The ‘optimum’ at 3.0% N may be suggested as an orientation point for growers.

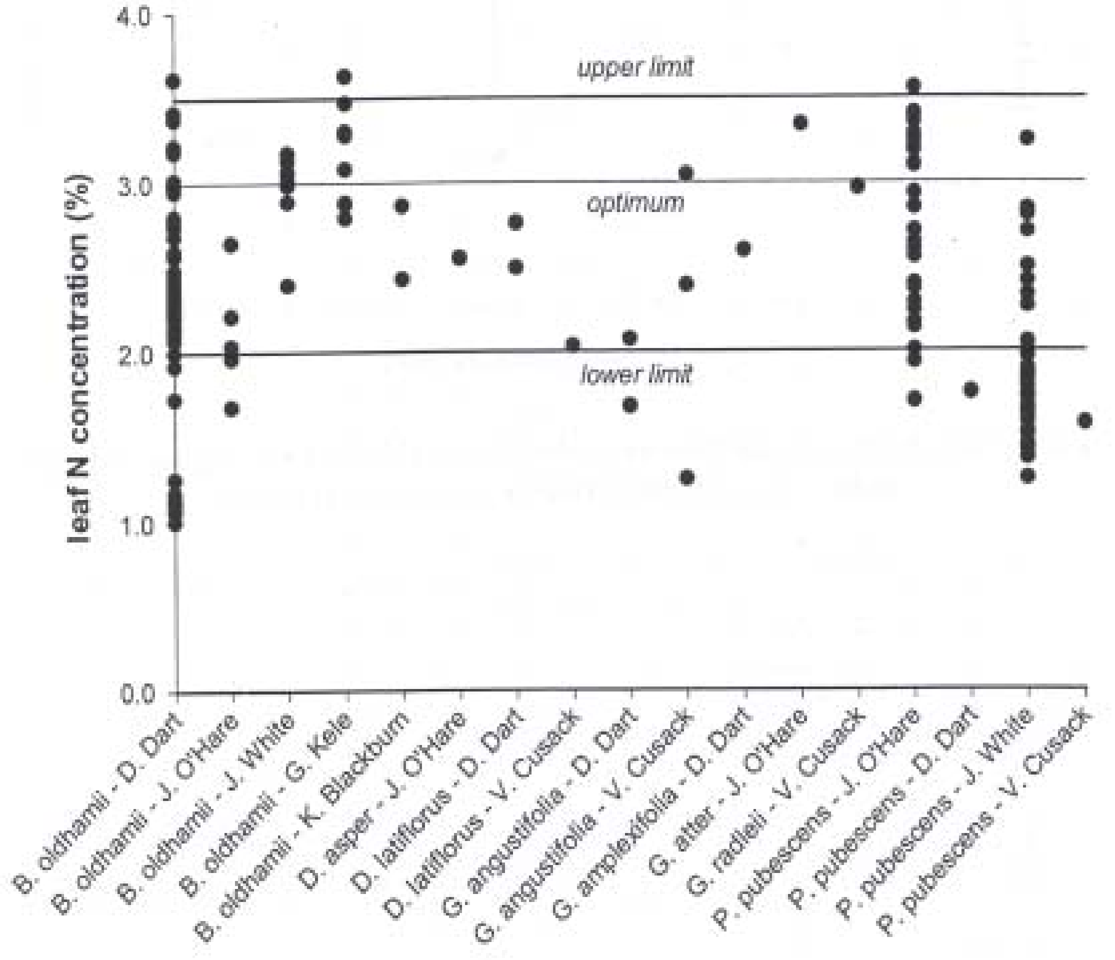

Figure 16 Leaf N concentrations in different bamboo species at various locations in Australia

In our studies with *B. oldhamii* and *P. pubescens*, leaf N did not decrease for about four months after application of nutrients. Therefore, 4-6 months could be a suitable time interval for analysing leaf N and accordingly applying nutrients. These events can be scheduled to coincide with the onset of distinct growth phases in bamboo, (1) the ‘shoot season’ and (2) the subsequent phase of rhizome growth. An additional measurement could be accommodated in (3) early spring for the clumping bamboos.

The response of fertilisation in leaf N 3-4 months after application was similar across the two bamboo species (Figure 17).

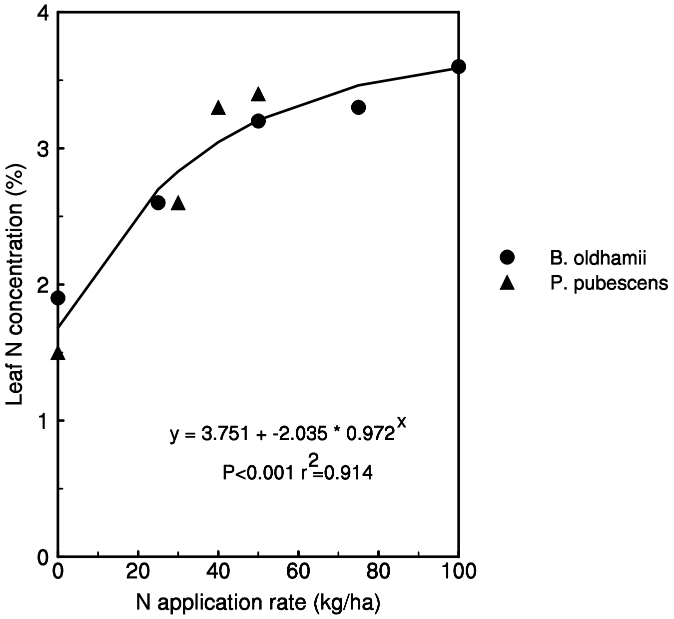

Figure 17 Relationship between N application rate and leaf N concentration in two bamboo species

The similarity in response to nutrient application in bamboo across species is not surprising. In comparison with plenty of other plant genera, it appears that the root system of bamboo is to an overwhelming percentage confined to a very shallow soil depth of about 40 centimetres in which it develops a root density that is much greater than in many other plants (Kleinhenz and Midmore, 2001)

This growth habit makes fertilisation in bamboo less affected by soil conditions and can explain our findings that under field conditions, bamboo is able to absorb nutrients up to very high rates.

The calculated hyperbola may be suggested as a guide to how much N fertiliser needs to be applied to raise N concentrations in bamboo leaves. The data points at 0 kg ha^{-1} N application represent the natural ‘fertility’, ie N mineralisation rate of the particular soil. The leaf-N value for *P. pubescens* was derived from the plantation in Dayboro and the value for *B. oldhamii* in Belli Park. The small differences in leaf-N values at 0 kg ha^{-1} N can be explained by soil ‘fertility’ which was lower in Dayboro but higher at Belli Park. The regression line indicates that relatively little N is required to lift leaf-N from low levels but more from higher levels. The equation estimates the theoretical maximum leaf-N concentration at 4.13 percent. Our suggested ‘optimum’ of 3.0 percent leaf N is at a level below which bamboo has a great affinity for N and above which plants respond only slightly to additional units of N application.

The following example resulting from our research with *B. oldhamii* may demonstrate a practical application of the suggested fertilisation strategy for farmers. When leaf N in unfertilised plants was 1.8 percent, (360 — 120 =) 240 kg ha^{-1} N was needed to raise leaf N to 3.0 percent. If leaf N would have dropped to 2.4 percent after 4-6 months, (360 — 180 =) 180 kg ha^{-1} N would have been required to raise leaf N back to 3.0 percent. From this, the total annual N application rate for 2-3 applications per year after the first year would sum up to about (2-3 × 180 =) 360-540 kg $ha^{-1}year^{-1}$N. This range confirms our first estimates for optimum fertiliser application in 1997.

We tested this DRIS application for different leaf-N levels (Control, 2.5, 3.0 and 3.5% N) in *B. oldhamii* in three sites, Belli Park, Dayboro and Iveragh. Size of clumps decreased in this direction as indicated by number of culms $clump^{-1}$ * culm diameter (Table 11).

Table 11 Clump parameters of *B. oldhamii* in the DRIS experiments at three sites

Location	Culm number (# $clump^{-1}$)	Culm diameter (cm)
Belli Park (D Dart)	8.0 ± 0.00	5.9 ± 0.14
Dayboro (J White)	14.1 ± 1.34	2.5 ± 0.14
Iveragh (J O'Hare)	9.0 ± 0.82	1.8 ± 0.12

N fertiliser rates were calculated based upon a first measurement of leaf N in November and were applied in early December. Across locations, average N application rates were 0, 64, 158 and 307 kg N ha-1 for the control treatment and target leaf N levels of 2.5, 3.0 and 3.5%. Figure 18 presents the course of leaf N of *B. oldhamii* at the three sites from November 1999 until March 2000. Leaf N principally increased with greater N application rates and target leaf N levels were nearly reached in December 1999, with the exception of the target level of 3.5% leaf N in Dayboro (Figure 18).

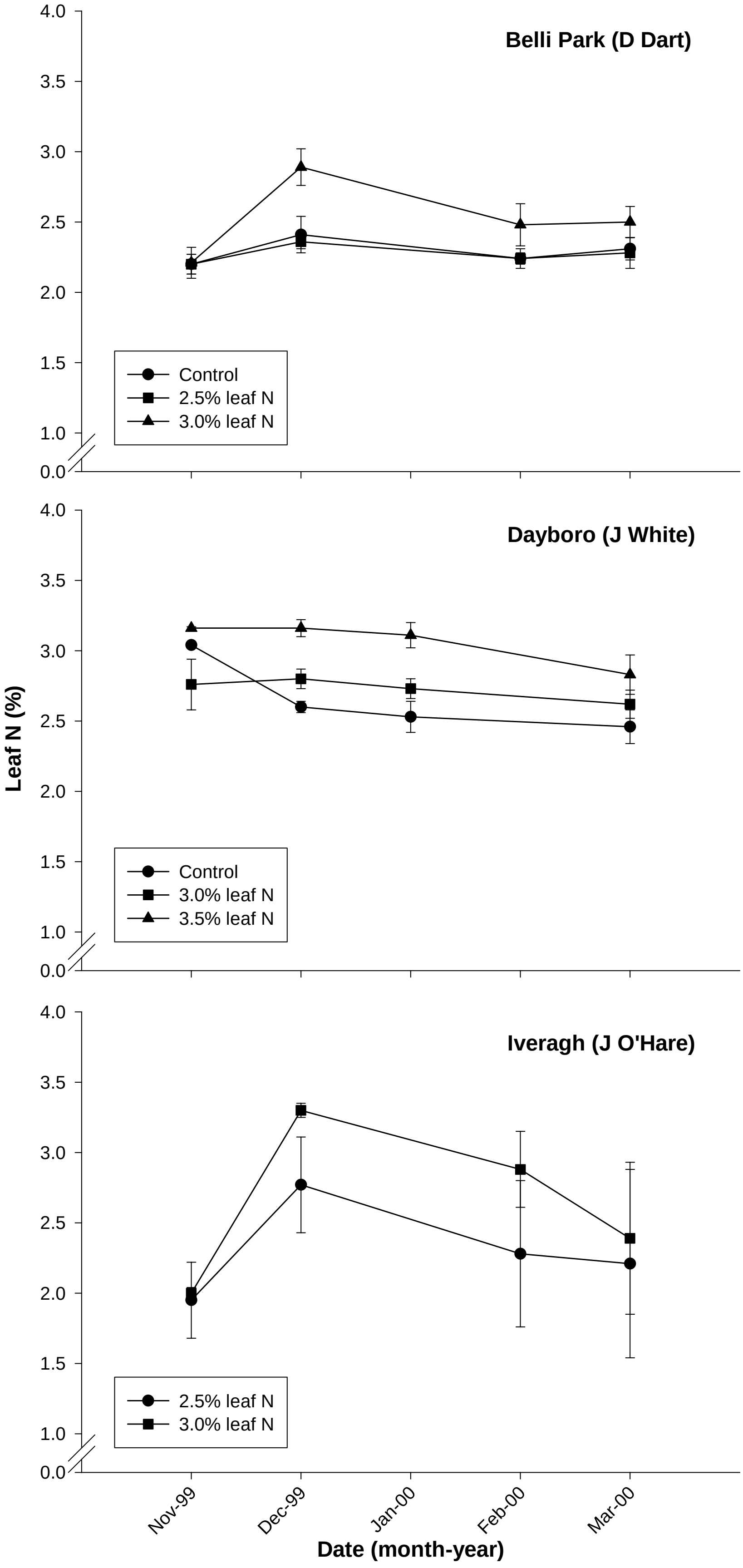

Figure 18 Course of leaf N concentrations at three sites for different leaf N target levels of *B. oldhamii*

Figure 19 shows the inverse relationship between number of culms and their diameter, in clumps not harvested for their shoots, as governed by the target N level. Higher N levels promote a greater number of new shoots whereas less N promotes their diameter. A target N level of just below 3.0% produced a balanced set of both number of shoots and their diameter.

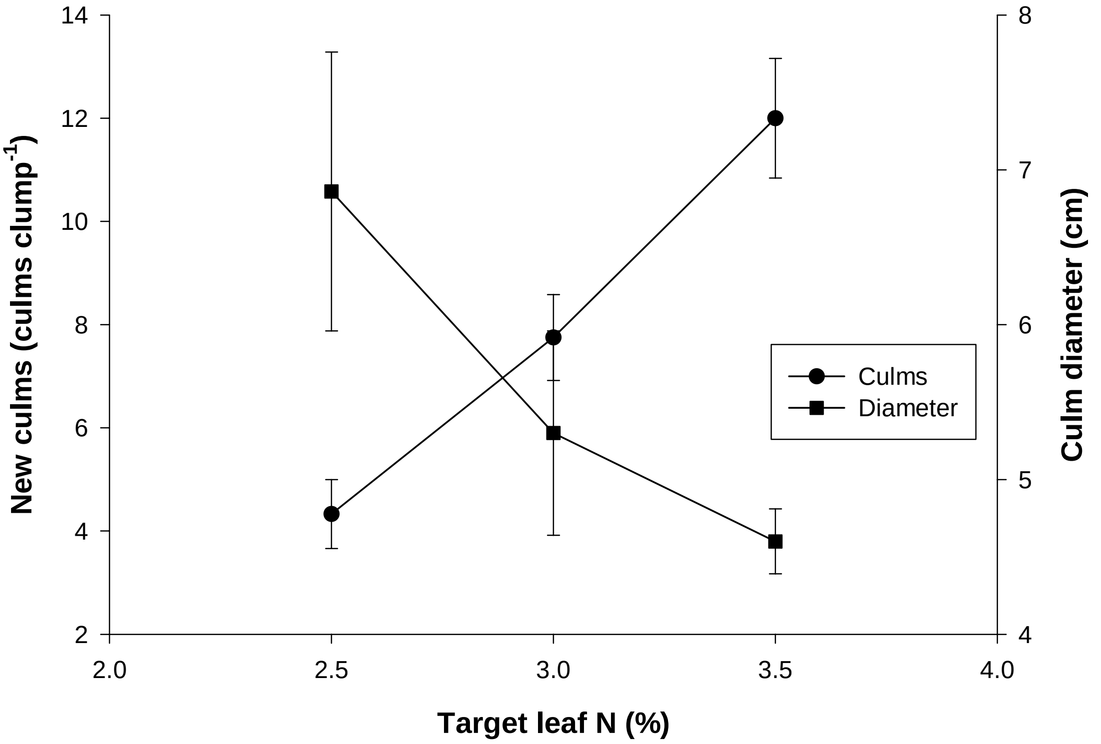

Figure 19 Number of new culms and their diameter as affected by leaf N target levels of *B. oldhamii*

Yield and shoot weight were only measured in the more mature bamboo stand at Belli Park. Differences between treatment means were not statistically different (Table 12)

Table 12 Number of new culms and their diameter as affected by leaf N target levels of *B. oldhamii* in Belli Park

Location	Marketable yield (t ha^{-1})	Shoot weight (kg shoot^{-1})
Control	3.20 a^{x}	0.65 a
2.5% leaf N	3.90 a	0.65 a
3.0% leaf N	3.87 a	0.61 a

^{x} Numbers followed by the same character are not significantly different (*P* = 0.05)

4.4 Usage of ions from wastewater

Details of bamboo cultivated in the wastewater facility in Rockhampton have been mentioned in sections 1.4 and 2.3. Table 13 presents data for element concentrations in leaves of *B. oldhamii* several months after having been transplanted to the sewage system. Many element concentrations increased significantly (exceptions were P, K, S, and Sr which significantly decreased), in spite of the greater size of plants over the same time frame.

Table 13 Element concentrations in *B. oldhamii* leaves grown in wastewater [a]

Element	October 1998	March 1999	Significance of change
As (ppm)	< 5	< 5	—
Cd (ppm)	< 0.5	< 0.5	—
Hg (ppm)	< 1	< 1	—
Pb (ppm)	< 3	< 3	—
B (ppm)	10.50 ± 1.500	12.67 ± 1.585	n.s.
Ba (ppm)	2.60 ± 0.400	2.67 ± 0.571	n.s.
Ca (%)	0.20 ± 0.011	0.19 ± 0.011	n.s.
Se (ppm)	4.50 ± 0.500	4.00 ± 0.577	n.s.
P (%)	0.25 ± 0.020	0.22 ± 0.012	*
K (%)	1.64 ± 0.018	1.62 ± 0.025	*
Al (ppm)	44.00 ± 2.000	144.50 ± 22.705	*
Co (ppm)	< 0.5	0.57 ± 0.033	*
Cr (ppm)	10.95 ± 0.950	30.82 ± 1.332	*
Cu (ppm)	10.24 ± 0.079	13.26 ± 0.438	*
Fe (ppm)	175.56 ± 5.546	433.94 ± 20.048	*
Mg (%)	0.18 ± 0.004	0.16 ± 0.006	*
Mn (ppm)	54.50 ± 1.500	63.17 ± 4.996	*
Mo (ppm)	3.50 ± 0.500	5.83 ± 0.307	*
Na (%)	0.02 ± 0.001	0.03 ± 0.003	*
Ni (ppm)	7.50 ± 0.600	20.55 ± 0.746	*
S (%)	0.22 ± 0.000	0.20 ± 0.008	*

Sr (ppm)	10.12 ± 0.271	8.90 ± 0.640	*
Zn (ppm)	24.51 ± 0.110	26.45 ± 1.574	*

[a] transplanted in July 1998

Box 3: Fertilizer requirements

The fast growth of bamboo, combined with the heavy level of harvesting of shoots and culms, puts a great demand on the soil to provide consistent quantities of nutrients for optimal growth. Nitrogen in the NH_4 form (such as from urea, or ammonium sulphate) was taken up more effectively then in the NO_3 (or nitrate, such as calcium nitrate) form but we also found that potassium is required by bamboo in similar quantity as those for nitrogen. Under greater irrigation application, there is greater response to added fertilizer nitrogen, but with a diminishing return relationship (the unit increase in yield with unit addition of nitrogen declines with every additional unit of nitrogen). Bamboo can absorb great quantities of nitrogen from the soil, and the leaf nitrogen is a good indicator of the nitrogen status of bamboo plants. Maintaining the % nitrogen in dried young leaves between 2-3.5%, with 3.0% considered optimum, should give a guide to the nitrogen demand by bamboo. A leaf nitrogen of 3% led to a balanced set of number and diameter of shoots in *B. oldhamii*.

5. Culm management

From 1997 to 2000, we conducted culm management experiments in an existing stand of *B. oldhamii* at Bamboo Australia, Belli Park. The treatment was ‘standing-culm density’ with four levels, 1,200, 2,400, 3,600 and 4,800 standing culms ha^{-1}. There were 400 clumps ha^{-1}, although Chinese recommendations for *B oldhamii* are 625 clumps/ha. Each plot comprised three clumps arranged in a one-factorial design with four replications. Only culms of up to 3 years of age were used and the number of culms for each age class was kept constant (ie 1-1-1, 2-2-2, 3-3-3 and 4-4-4 culms of 1-2-3 years of age).

Each year, the number of felled standing culms (excess new culms and all 4-year old culms) was recorded. Since it was too laborious to determine directly, their biomass was estimated by sampling in 2000 (Table 14). The greater biomass of the 4-years old culms was to the greater part due to the higher specific gravity which was caused by their lower water content (data not shown). Those estimates did not account for increases in culm length and diameter with stand age.

Table 14 Estimates for biomass of single culms of different age (*B. oldhamii*) at Belli Park

Parameter	<1-year old culm	4-years old culm
Specific gravity (kg m^{-3})	673 ± 24.1	893 ± 13.8
Base diameter (m)	0.079 ± 0.0074	0.064 ± 0.0025
Length (m)	11.8 ± 0.22	12.6 ± 0.81
Volume (m^3)	0.020 ± 0.0040	0.014 ± 0.0015
Fresh weight (kg)	13.6 ± 2.70	17.4 ± 4.31

During the shoot season of each year, total yield of fresh edible shoots and their weight were recorded. Maximum yields increased from 0.9 t ha^{-1} in 1998 to 1.4 t ha^{-1} in 1999 to 2.5 t ha^{-1} in 2000 (Figure 20). The lowest standing-culm density (1,200 culms ha^{-1}) performed least in 1998, best in 1999 and least in 2000 again. In contrast, the highest standing-culm density (4,800 culms ha^{-1}) was the best treatment in 1998 but the worst in 1999. The medium high standing-culm densities (2,400 and 3,600 culms ha^{-1}) performed more stable between years.

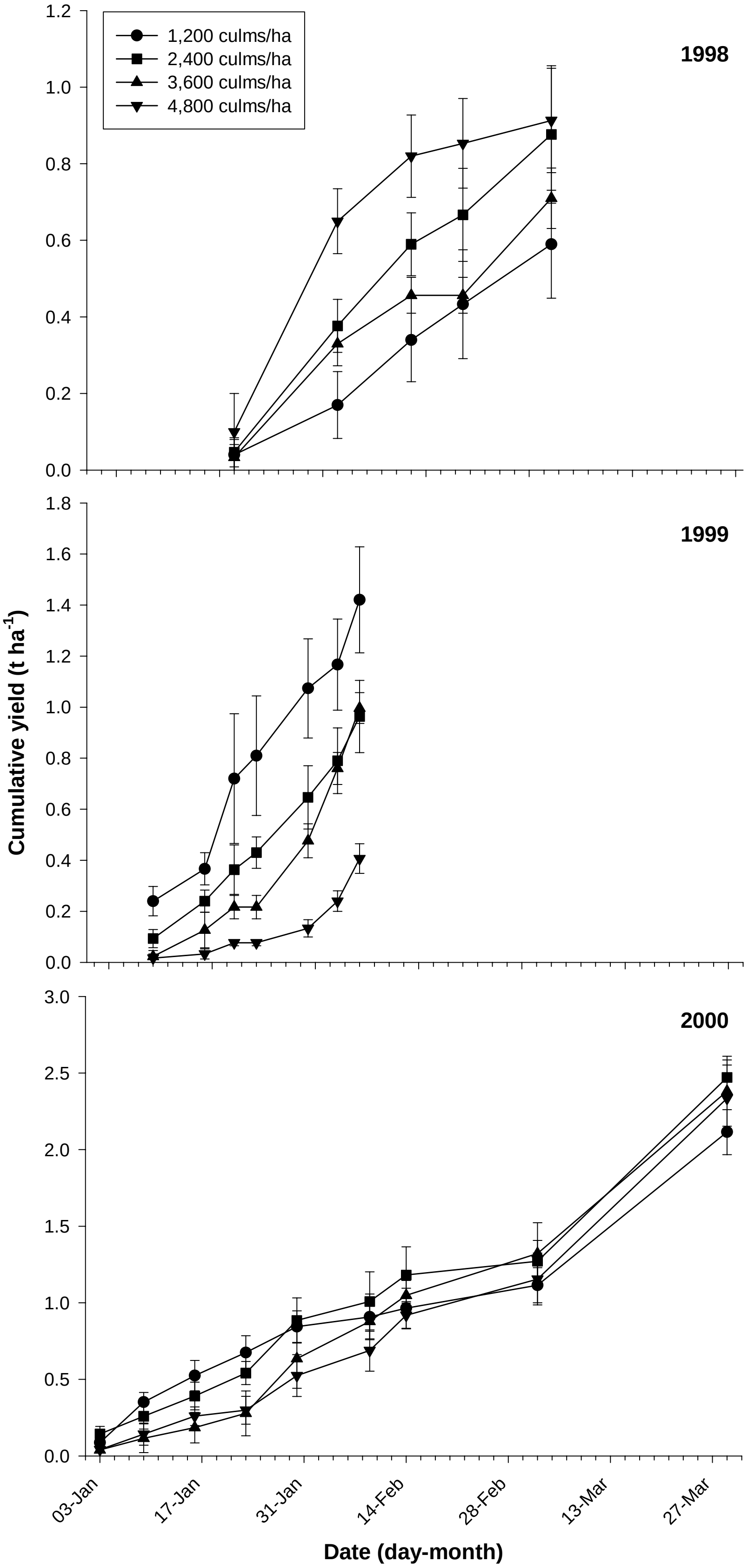

Figure 20 Effect of standing-culm density on cumulative shoot yield of *B. oldhamii* at Belli Park 1998-2000

In addition to marketable yields, Table 15 presents data for number of harvested bamboo shoots and for shoot weight. Although differences were usually not significant, there was a trend that greater shoot numbers resulted in less shoot weight. It appears that management techniques that promote greater shoot numbers result in higher yields but reduced individual shoot yield (see sections 4.2 and 4.3). The yearly increases in yield were due to a greater number of shoots harvested rather than increases in shoot weight. Differences in total yield, number of shoots and average shoot weight were statistically not significant but there was a trend that yield of fresh, edible bamboo shoots was promoted by lower standing-culm density.

Table 15 Harvested shoot number and shoot weight as affected by standing-culm density of *B. oldhamii* at Belli Park 1998-2000

Standing-culm density	Marketable yield ($t\ ha^{-1}$)	Number of shoot ($\#\ ha^{-1}$)	Shoot weight (g)
1998			
1,200	0.59 a[x]	1,300 a	0.46 b
2,400	0.88 a	1,700 a	0.55 ab
3,600	0.71 a	1,067 a	0.67 a
4,800	0.91 a	1,767 a	0.51 b
1999			
1,200	1.42 a	2,700 a	0.55 a
2,400	0.96 b	2,233 a	0.43 a
3,600	1.00 b	2,233 a	0.45 a
4,800	0.41 c	1,167 b	0.35 a
2000			
1,200	2.12 a	3,900 a	0.49 a
2,400	2.47 a	4,100 a	0.59 a
3,600	2.38 a	3,867 a	0.61 a
4,800	2.34 a	3,700 a	0.60 a

TOTAL [a]			
1,200	4.13 a	7,900 a	0.50 a
2,400	4.31 a	8,033 a	0.52 a
3,600	4.09 a	7,167 a	0.58 a
4,800	3.66 a	6,633 a	0.49 a

[a] Total yield and number of shoots, average shoot weight

[x] Numbers followed by the same character within a year are not significantly different (*P* = 0.05)

Table 16 presents the effect of standing-culm density on timber yields. Understandably, yield of 4-years old culms increases significantly with standing-culm density since more culms were allowed to mature at greater density. However, the opposite was true for culms <1 year old: yield was higher at lower standing-culm density. This reflected the farmer's practice of ensuring survival of required new culms by allowing culms in excess to elongate. Four-years old culms of sympodial species such as the *B. oldhamii* of this experiment have reached maturity for multipurpose timber use. However, the use of <1-year old culms is more restricted and they are particularly suited to pulping and papermaking, for culms from one to six years old may be used as raw material for pulping (Shanmughavel and Francis, 2001).

Table 16 Yield of culms of different age for timber as affected by standing-culm density of *B. oldhamii* at Belli Park 1998-2000

Standing-culm density	<1-year old culms (t ha^{-1})	4-years old culms (t ha^{-1})	All culms (t ha^{-1})	Culm diameter (cm)
1998				
1,200	27.2 ab[x]	5.8 c	33.0 b	5.60 c
2,400	23.1 b	13.3 b	36.5 b	6.38 ab
3,600	23.1 b	18.0 ab	41.1 b	6.48 a
4,800	32.6 a	19.7 a	52.4 a	5.83 bc
1999				
1,200	20.4 a	7.0 d	27.4 a	6.88 a
2,400	18.6 a	12.8 c	31.4 a	6.96 a
3,600	10.4 b	18.6 b	29.0 a	7.11 a
4,800	7.7 b	24.9 a	32.7 a	7.13 a

2000				
1,200	18.6 a	7.0 d	25.6 b	6.43 b
2,400	17.2 a	15.1 c	32.3 a	6.74 b
3,600	9.5 b	20.9 b	30.4 ab	7.51 a
4,800	2.3 c	28.4 a	30.7 ab	7.63 a
TOTAL				
1,200	66.2 a	19.7 d	85.9 b	6.30 b
2,400	58.9 a	41.2 c	100.1 ab	6.69 ab
3,600	43.1 b	57.4 b	100.5 ab	6.86 a
4,800	42.6 b	73.1 a	115.7 a	7.03 a

[X] Numbers in a column followed by the same character within a year are not significantly different (P = 0.05)

The diameter of harvested culms was only determined for the <1-year old culms. Table 16 shows that except in the first year after imposing treatments, there was a trend that higher standing-culm density favoured greater culm diameter.

Besides other possible parameters, the optimal standing-culm density depends on the farmer's preference for the four yield and quality parameters: (1) shoot yield, (2) shoot quality (ie shoot weight), (3) timber yield (4-years old culms) and (4) timber quality (ie culm diameter). Figure 21 presents a summary of the effects of standing-culm density on these parameters. The intersect between curves described optima between combinations of parameters. Shoot production, ie shoot yield and weight, was optimal at a standing-culm density of 3,150 culms ha^{-1} and so was yield (ie shoot yield and timber yield). The optimum for quality, ie shoot weight and culm diameter, was at a standing-culm density of 3,600 culms ha^{-1} and that of timber production (timber yield and culm diameter) at 3,725 culms ha^{-1}. These results indicate that the overall optimal standing-culm density was around 3,600 culms ha^{-1} or 3-3-3 culms of 1-2-3 years of age.

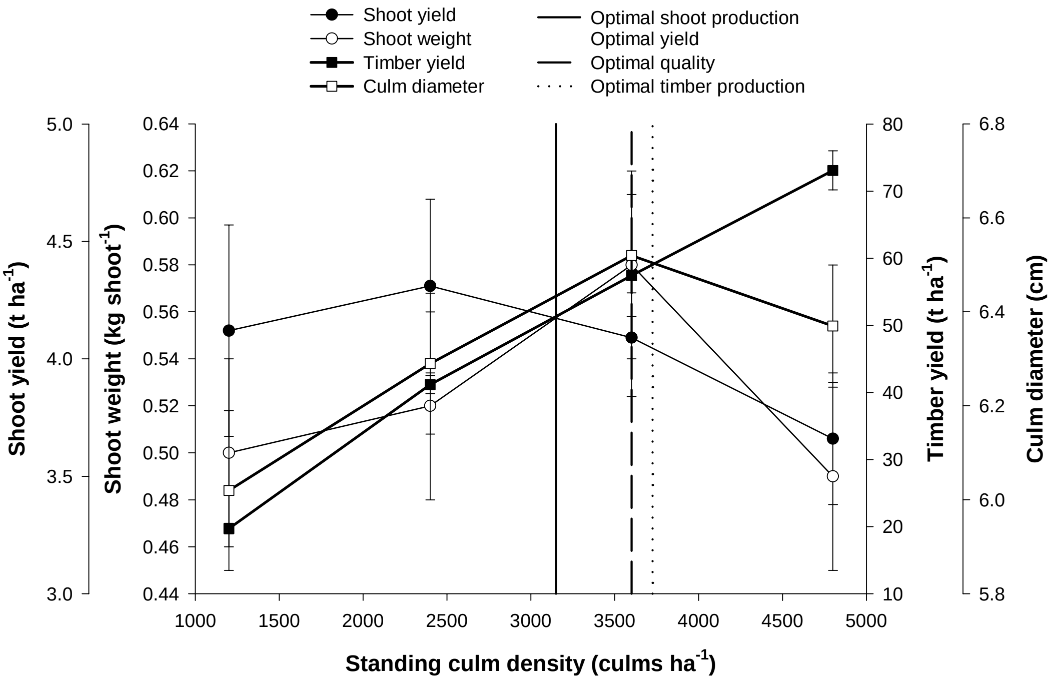

Figure 21 Yield and quality of bamboo products as affected by standing culm density and optima for combinations of parameters (total yield and average quality of *B. oldhamii* at Belli Park 1998-2000)

A study of light transmission through the bamboo canopy in the different treatments revealed a possible reason for better bamboo growth at the standing-culm density of 3,600 culms ha^{-1} (Figure 22). Light interception by the bamboo canopy increased up to the standing-culm density of 3,600 culms ha^{-1} and decreased slightly thereafter.

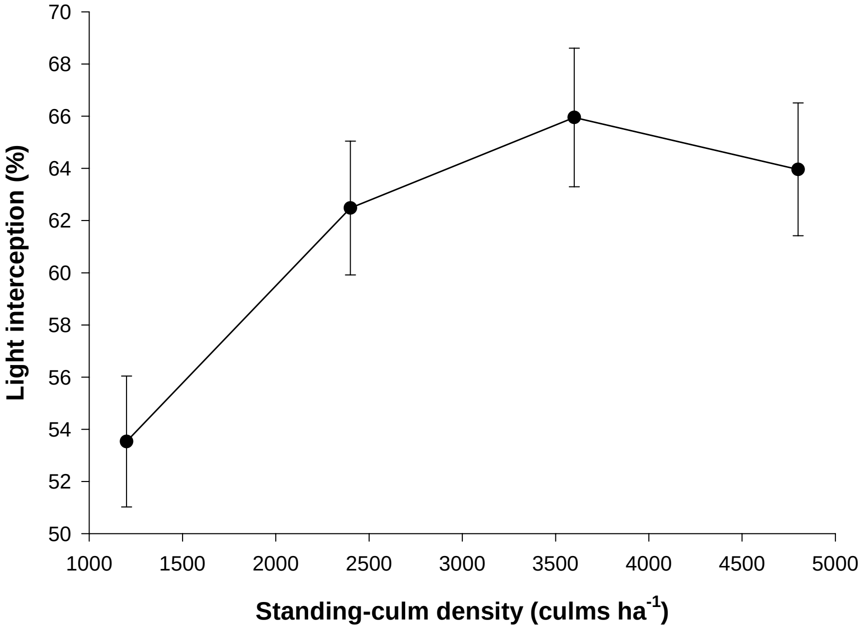

Figure 22 Light interception by bamboo canopy of *B. oldhamii* at different standing-culm density at Belli Park, 2000

In a review on bamboo agronomy, Kleinhenz and Midmore (2001) summarised that standing-culm density varies according to bamboo product: standing-culm density in plantations managed primarily for shoots-only average higher than in plantations for both shoots and timber. Greatest standing-culm densities are apparent in timber-only stands. This relationship could be confirmed for our study, shoot yields were better at lower standing-culm density whereas timber yields were higher at greater standing-culm density.

Several authors (eg Sagwal, 1987) have described an inverse relationship between yield and diameter of shoots and culms, which is determined by standing-culm density. Usually, lower standing-culm densities promote diameter but reduce total yield. On the other hand, higher standing-culm densities increase total yield but reduce diameter of shoots and culms. In our study, this relationship could not be confirmed for fresh bamboo shoots and for timber only at standing-culm density over 3,600 culms ha^{-1}. As mentioned before, greater yields in our studies were predominately due to greater shoot (culm) numbers rather than shoot (culm) weight (diameter). It appears that the inverse relationship between shoot (culm) number and shoot (culm) weight (diameter) governed by standing-culm density had a limiting effect on increases of yield of fresh shoots with increasing standing-culm density.

It can only be speculated as to whether it would be advantageous to modify the number of standing culms according to their age. We only tested a constant number of culms in different age classes and there is indication that it might be beneficial to decrease the number of standing culms with age (eg 4-3-2 culms of 1-2-3 years of age). Over a period of three months, we measured the photosynthetic rate of leaves of the same age on culms of different age in *B. oldhamii* and detected a decrease with increasing culm age (Figure 23). In contrast to dicotyledonous plants, conducting tissues of bamboo have to function for many years without the formation of any new tissue (Liese, 1995). Furthermore, dicotyledonous trees can shed or deposit metabolic residue substances, but such substances accumulate in metaxylem vessels (eg tyloses and slime substances) and sieve tubes (eg callose) of bamboo culms (Liese, 1991). This progressively decreases the conductivity of the xylem for water and nutrients and that of the phloem for assimilates. Therefore, photosynthesis of leaves on older culms will be less since water supply is increasingly restricted and export of the lower quantity of photosynthates to growing tissues such as newly emerging culms will be reduced.

Box 4: Thinning and culm management

An experiment with *B. oldhamii* with various thinning regimes (keeping culms to ensure one, two or three culms of each of one two and three years of age) aimed to determine the optimum culm population for shoot weight and culm diameter and timber production for the latter, the optimal population was 3725 culms ha^{-1}, and for shoot production at 3600 culms ha^{-1}, or a 3-3-3 culms of 1-2-3 years of age in a stand of 400 clumps ha^{-1}. Our data on photosynthesis (the production of carbohydrate from carbon dioxide, water, and light energy) suggest that the productivity of older culms is less than that of younger culms, in *B. oldhamii*, and that in fact 4-3-2 culms of 1-2-3 years of age might be more suitable, but research to quantify this at the plantation level is lacking.

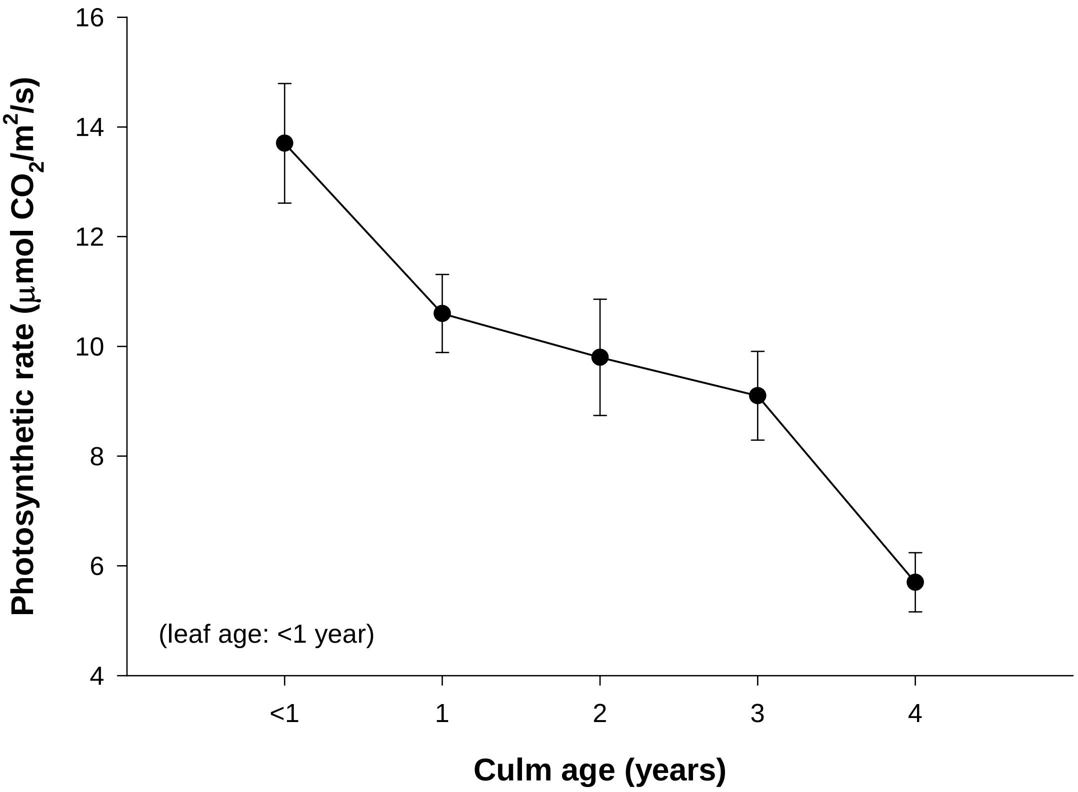

Figure 23 Photosynthetic rate of <1-year old leaves on culms of different age of *B. oldhamii* at Rockhampton 1999-2000

6. Postharvest

Three fundamental processes of quality loss in fresh bamboo shoots after harvest include (1) weight loss through transpiration, (2) weight loss through respiration and (3) discolouration and fungal infection. Practices to reduce weight loss and minimise discolouration and fungal infection include packaging and cooling. Generally, there are two parameters of ‘cooling’ which affect shelf-life of horticultural commodities: the optimal storage temperature and how quick the temperature of the produce is reduced to that storage temperature.

6.1 Surface-to-weight relationship

As for any other horticultural commodity held in storage, transpiration and heat conductance in bamboo depend on the relationship between weight and surface area of their shoots. The shape of a bamboo shoot roughly resembles the shape of a cone. The base surface of a cone is $S_b = \pi r^2$, the lateral surface $S_l = \pi r \sqrt{r^2 + h^2}$, and the total surface $S_b + S_l$. We measured weight and volume of a variety of bamboo shoots from different species and found a highly significant relationship between the surface/weight ratio and shoot weight (Figure 24). As shoots increase in weight, the degree of hollow space increases (starting when the length to diameter ratio exceeds 3.5/4:1), reducing significantly the propation of harvestable shoot material vs. waste and leaf matter (ACBC, pers com.). Such an effect, though, did not impact on the relationship observed in Figure 24.

The ratio decreased exponentially with shoot weight indicating that transpiration and heat conductance would be relatively lower in heavier (bigger) shoots. Therefore, 'storability' of bamboo shoots depends on shoot weight and the relative importance of (1) transpiration and (2) temperature-governed factors such as respiration and decay through microbial activity.

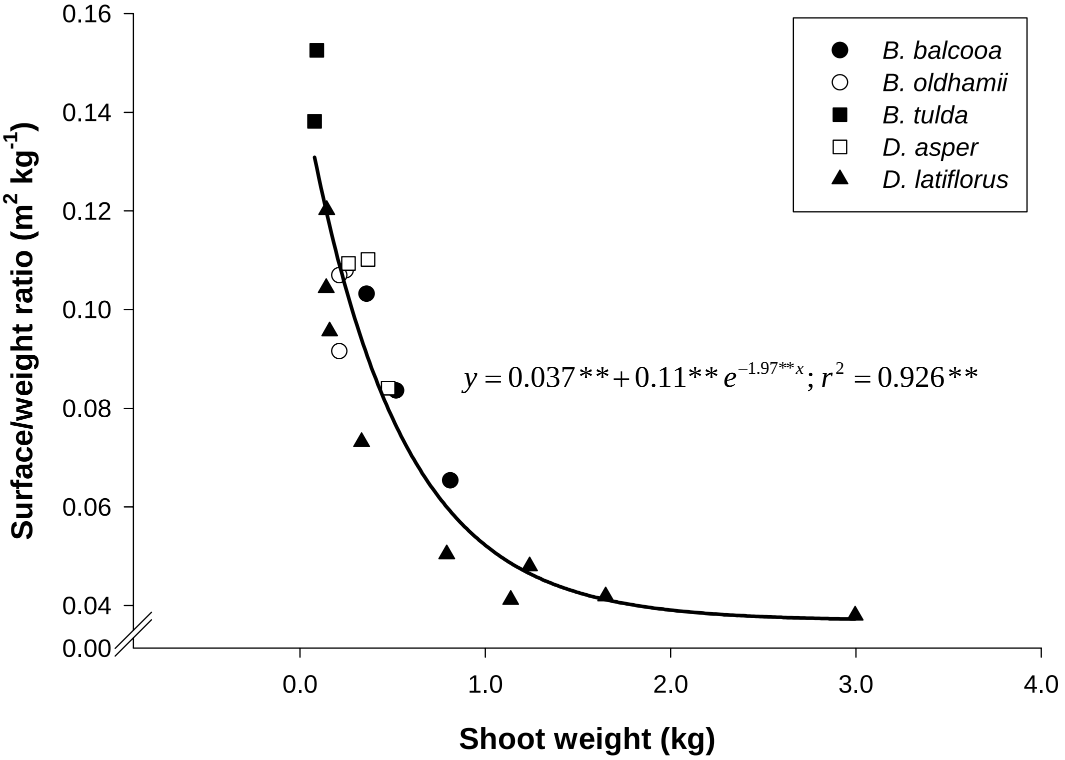

Figure 24 Surface-to-weight ratio in bamboo shoots of different species as affected by shoot weight

6.2 Weight loss by shoot part

For this study we sealed (1) the lateral surface, (2) the base surface or (3) the total surface of bamboo shoots with low density polyethylene (LDPE) film and stored them in the air (>95% relative humidity) for 28 days at 1°C.

Up to 21 days after harvest, there was greater weight loss through the open wound at the base surface. This may be attributed to the damage of the protective surface cell layer and exposure of underlying tissues to the atmosphere (Figure 25). After 21 days of storage, there was a non-significant trend towards greater loss through the lateral surface. This may be due to progressive sealing of the base part by dead cells.

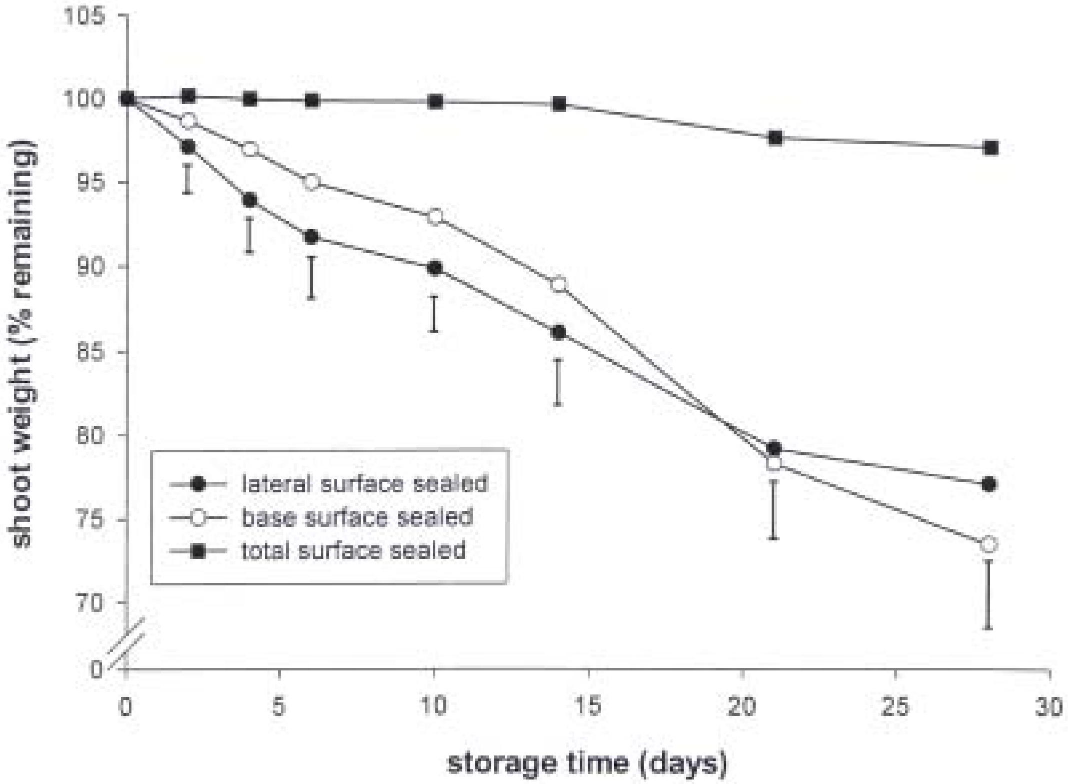

Figure 25 Weight loss from different parts of *B. oldhamii* shoots during storage at 1° C (vertical bars indicate LSDs)

6.3 Storage temperature

All shoots for a study comparing storage temperatures were packaged in macro-perforated LDPE bags. Generally, shoots that had lost more than 5% of their initial weight were visually rated as unacceptable to the market. When weight loss progressed beyond this stage, the cut ends of shoots desiccated and cracks appeared. Subsequently, the lateral surface became pale in colour and shrivelled.

Weight loss of bamboo shoots was accelerated by higher storage temperature (Figure 26). Weight decreased linearly with storage period but the rate of weight loss at 25°C was disproportionately greater to that at lower temperatures. The linear shape of curves made it possible to extrapolate shelf life of bamboo shoots based on a critical weight loss of 5%. At 1, 8, 11 and 25°C, shoots lost 5% of their weight within approximately 17, 10, 5 and 1 day(s), and these periods corresponded to their shelf lives. All differences in weight loss between storage temperatures were significant as indicated by standard errors.

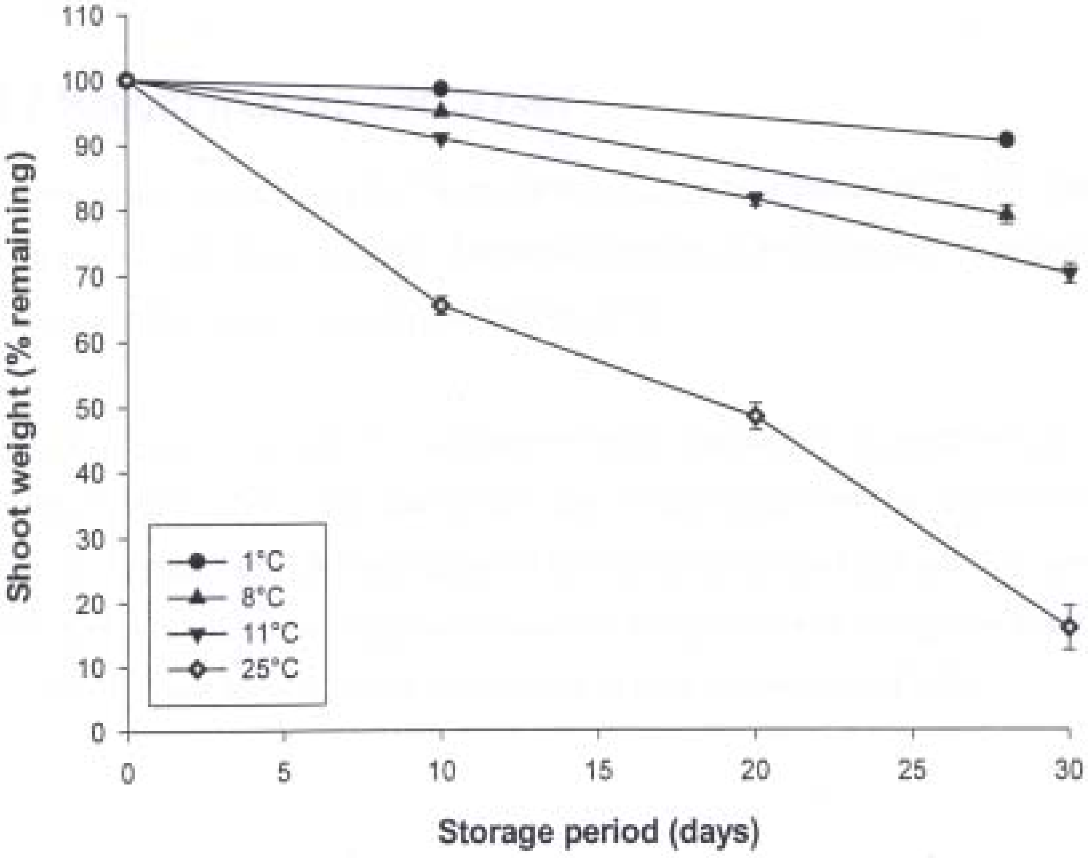

Figure 26 Weight loss of bamboo shoots (*B. oldhamii*) as affected by storage temperature

6.4 Packaging

During the storage experiments conducted at CQU, Rockhampton and at DPIF-NT, Darwin, the following materials were tested:

Open storage (control)

Low-density polyethylene (LDPE) film (10.5 µm thick)

Macro-perforated LDPE bags (45 µm thick, 8.94% perforation)

Micro-perforated LDPE bags (35 µm thick, 0.01% perforation)

LDPE bags (45 µm thick)

Heat-sealed, food grade polyvinyl chloride (PVC) film (90 µm thick).

Weight loss of packages (bamboo shoots and their packaging materials) reflected the permeability of the five different materials at 1°C (Figure 27). After 6 days of storage, weight loss of shoots in macro-perforated LDPE bags was significantly greater than in all other materials. After 22 days, weight loss of shoots in micro-perforated LDPE bags and LDPE film exceeded that of shoots in LDPE bags and heat-sealed PVC. Therefore, packaging materials could be categorised into three groups: low-permeable materials (heat-sealed PVC film and LDPE bags), medium-permeable materials (LDPE film and micro-perforated LDPE bags), and highly permeable material (macro-perforated LDPE bags).

As a reference, a control treatment with shoots stored open was included. Even at the low storage temperature of 1°C, bamboo shoots stored open lost 7.67% weight within 10 days (Table 17) and their shelf life of was no more than 7 days. Packaging in any material significantly reduced this weight loss.

Table 17 Influence of packaging material on TOTAL (%) weight loss of bamboo shoots (*B. oldhamii*) stored at 1°C after different storage periods

Packaging material	Storage period	
	10 days	28 days
Control (open storage)	7.67a[x]	26.96a
Macro-perforated LDPE bag	1.80b	9.85b
Micro-perforated LDPE bag	0.22b	4.97c
LDPE film	0.37b	5.58c
LDPE bag	0.09b	4.17c
Heat-sealed PVC film	1.59b	5.96c

[x] Numbers followed by the same character are not significantly different (*P* = 0.05)

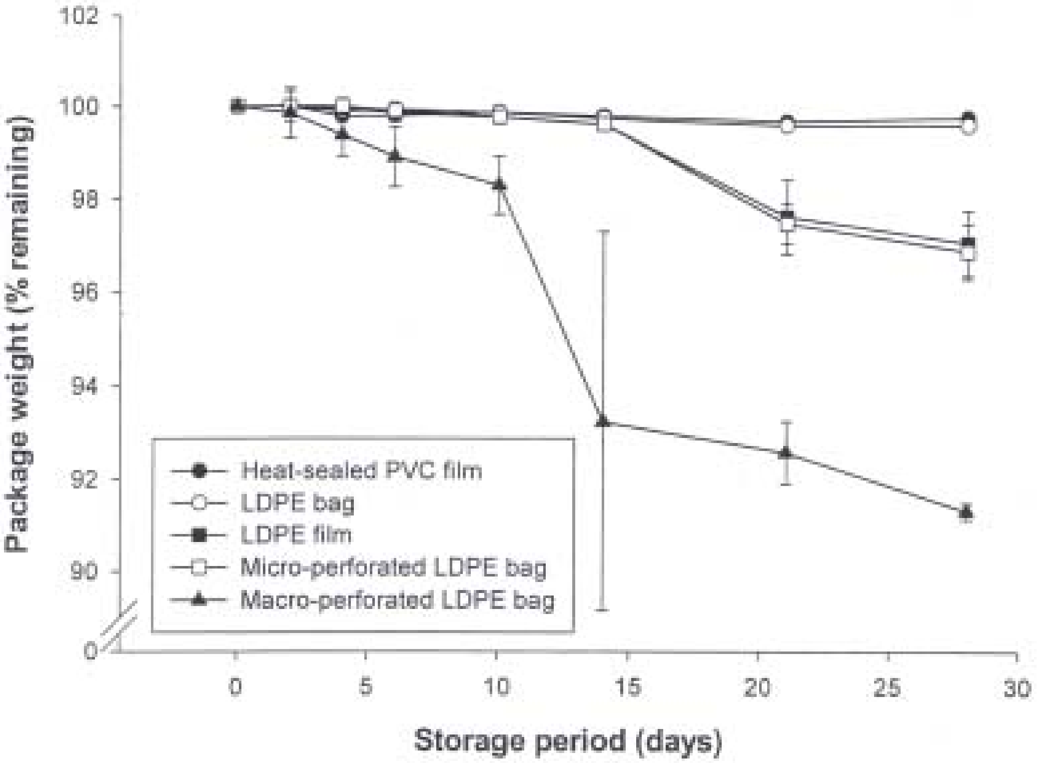

Figure 27 Weight loss of packages of bamboo shoots (*B. oldhamii*) stored at 1°C as affected by packaging materials

The total weight loss of bamboo shoots could not be completely explained by the differences in permeability of packaging materials. After 10 days of storage, the weight loss of bamboo shoots through the macro-perforated LDPE bags was significantly greater than through all other materials (Figure 27) but the total weight loss (Table 17) was not. After 28 days, the greater permeability of the macro-perforated LDPE material was reflected in total weight loss of bamboo shoots. However, there were no significant differences between weight loss in all other materials, i.e. no differences between materials which were categorized as semi- and low-permeable. When considering desiccation only, shelf life of bamboo shoots stored in those materials extended to the full storage period of 4 weeks. The differences between weight loss through the packaging materials and total weight loss could be explained by weight loss from shoots (ie as condensation) within the materials. Bamboo shoots stored in less permeable materials lost a greater percentage of their initial weight within those materials as indicated by greater ratios of internal/external weight loss (Table 18). Higher values of this ratio corresponded to greater condensation within packaging materials.

Table 18 Influence of packaging material on the relationship between weight loss of bamboo shoots (*B. oldhamii*) stored for 28 days at 1°C to the inside and outside of package

Packaging material	Internal/external weight loss
Macro-perforated LDPE bag	0.07b[x]
Micro-perforated LDPE bag	0.51b
LDPE film	1.16b
LDPE bag	9.01b
Heat-sealed PVC film	25.33a

[x] Numbers followed by the same character are not significantly different (*P* = 0.05)

This was particularly so for the heat-sealed PVC film and to a lesser degree for LDPE bags. Although shoots in heat-sealed PVC film did not loose significantly more weight than shoots in the medium-permeable materials (Table 17), a significantly greater percentage of this loss occurred within packages. If bamboo shoots were to be marketed individually packaged in heat-sealed PVC film or LDPE bags, the deterioration of visual quality of packages by condensation water would have reduced shelf life to about 14 and 21 days, respectively.

6.5 Respiration

Respiration rates of bamboo shoots were strongly affected by storage temperature (Figure 28). Except for immediately after harvest when temperature treatments had barely been imposed, respiration was significantly greater in bamboo shoots stored at 20°C than at 2°C, irrespective of packaging. At 2°C, the respiration rate of shoots was about 34 ml CO_2 kg^{-1} h^{-1} after harvest and declined significantly to reach an equilibrium of 10 ml CO_2 kg^{-1} h^{-1}. At 20°C, there was an immediate increase in respiration rate at 1 day reaching 142 and 94 ml CO_2 kg^{-1} h^{-1} for shoots with LDPE film and shoots stored in the open, respectively. These peaks were followed by a rapid decrease on day 2 and a slow decrease thereafter. Packaging had no effect on respiration at 2°C, but at 20°C rates were significantly greater in the shoots with LDPE film on day 1 and 2 after harvest.

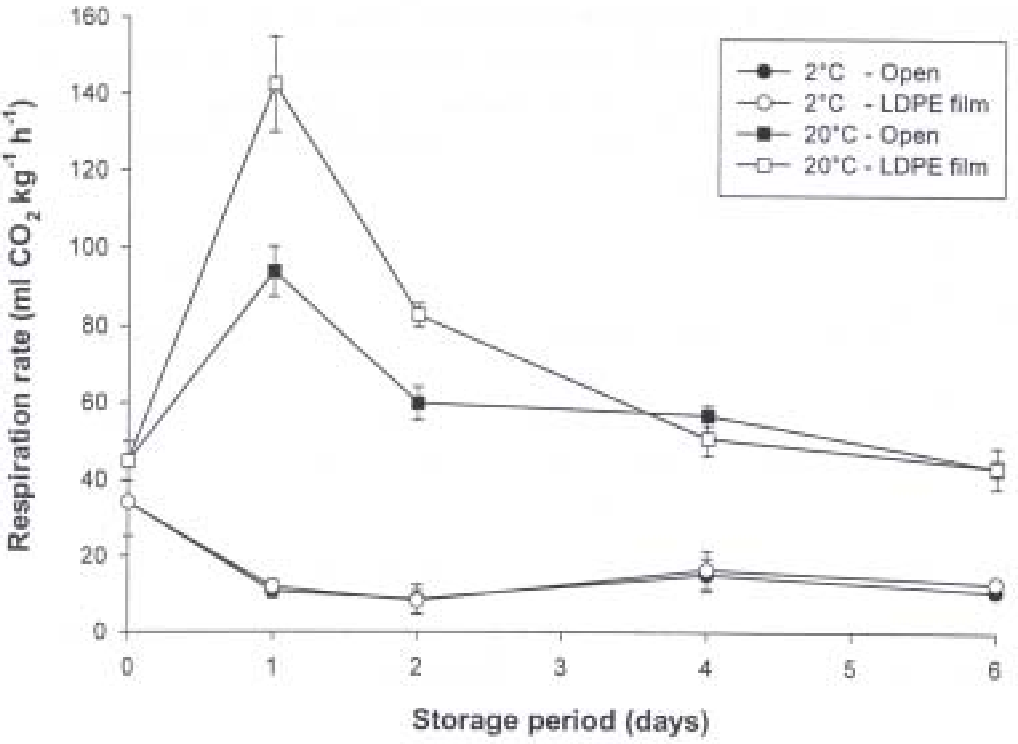

Figure 28 Respiration rate of bamboo shoots (*B. oldhamii*) as affected by storage temperature and packaging

Weight loss by respiration after 6 days storage period was calculated taking glucose as the primary respiratory substrate and assuming constant evolution of CO_2 at the average of measured respiration rates. Weight loss by transpiration was calculated by subtracting respiratory weight loss from the measured total weight loss. Bamboo shoots which were stored open lost 23.5 ± 0.58% of their weight at 20°C after 6 days storage (Table 19). To reduce this weight loss, packaging had a stronger effect than lower temperature: total weight loss of shoots at 20°C with LDPE film was significantly lower than weight loss of shoots at 2°C without LDPE film. However, a combination of both LDPE film and low temperature (2°C) reduced weight loss significantly to the lowest value recorded (Table 19). When shoots were stored without LDPE film, respiration accounted for only small percentages of total weight loss at both storage temperatures. In contrast, respiration accounted for 18 and 34% of total weight loss for shoots stored with LDPE film at 2 and 20°C, respectively.

Table 19 Influence of storage temperature and packaging on weight loss of bamboo shoots (*B. oldhamii*) by respiration and transpiration (mean ± S.E.) after 6 days storage

Storage conditions	Average Respiration rate (ml CO_2 kg^{-1} h^{-1})	Weight loss (% of initial)			Respiration/ Total (%)
		Respiration	Transpiration	Total	
2°C					
Open	15.8 ± 3.95	0.26 ± 0.065	4.4 ± 0.20	4.7 ± 0.26	6 ± 1.3
LDPE film	16.6 ± 3.83	0.27 ± 0.062	1.3 ± 0.34	1.5 ± 0.40	18 ± 2.8
20°C					
Open	59.7 ± 4.76	0.96 ± 0.075	22.6 ± 0.52	23.5 ± 0.58	4 ± 0.2
LDPE film	72.7 ± 5.42	1.17 ± 0.087	2.2 ± 0.08	3.4 ± 0.14	34 ± 1.1

6.6 Discolouration and fungal infection

External discolouration and fungal infection was visually assessed for bamboo shoots stored at 1°C in the various packaging materials and at 8°C in LDPE bags after 2, 4, 7, 10, 14, 21 and 28 days storage period in the experiment at CQU in 1999. Discolouration was rated on a 5-point scale (where 0 = bleached white surface colour, 1 = some yellow stain, 2 = some dark spots, 3 = moderately discoloured and 4 = highly discoloured). Fungal infection was rated as the percentage of surface of shoots covered with fungal mycelia: 0 = 0% to 4 = 100% surface cover.

The highest scores (ie the least quality) for discolouration and fungal infection of bamboo shoots were recorded at the higher storage temperature (Figure 29). After 6 days of storage, brownish-black spots appeared on shoots stored at 8°C and developed into dark, soft patches. After 4 weeks, these shoots were completely discoloured whereas shoots at 1°C had only few yellow stains. There was no apparent fungal growth on bamboo shoots stored at 1°C throughout the storage period. However, starting 1 week after the first signs of discolouration on shoots at 8°C, fungal mycelia rapidly developed and covered the entire surface of some shoots after 4 weeks (Figure 29). Based upon discolouration and fungal infection, shelf life of bamboo shoots stored at 1°C was possible for more than 28 days (only few yellow stains), and for those stored at 8°C for less than 10 days (dark brown spots all over). The influence of packaging materials (assessed only at 1°C) was not significant (data not shown).

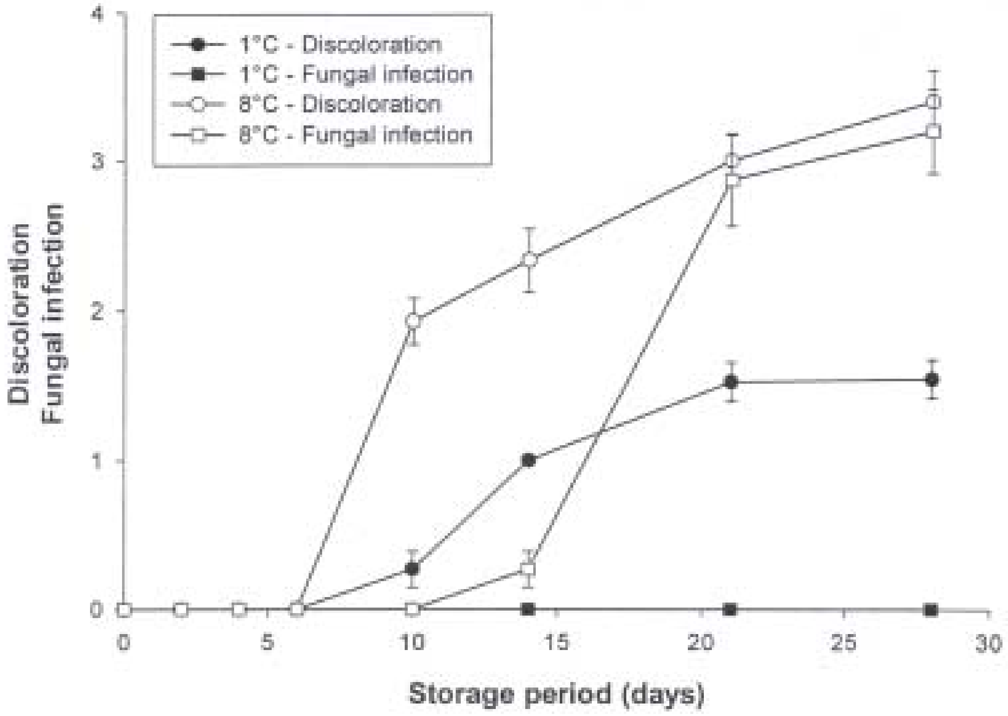

Figure 29 External discolouration and fungal infection of bamboo shoots (*B. oldhamii*) stored in LDPE bags at 1°C

6.7 Shelf life

When considering all measured quality parameters (ie weight loss, discolouration, fungal infection and condensation), shelf life of bamboo shoots was possible for no more than 7 days at storage temperatures above 8°C (Table 20).

Table 20 Influence of packaging material and storage temperature on shelf life (days) of bamboo (*B. oldhamii*) shoots (data collated from all experiments)

Packaging material	Storage temperature					
	1°C	2°C	8°C	11°C	20°C	25°C
Control (open storage)	7	6	—[a]	—	1.5	—
Macro-perforated LDPE bag	17	—	6-10	5	—	1
Micro-perforated LDPE bag	28	—	—	—	—	—
LDPE film	28	20	—	—	6	—
LDPE bag	21	—	6-10	—	—	—
Heat-sealed PVC film	14	—	—	—	—	—

[a] not assessed

At lower temperatures, packaging extended shelf life beyond the 6 days possible without packaging. The optimum packaging units at 1°C were the semi-permeable materials (micro-perforated LDPE bag and LDPE film) in which shelf life could be extended to and possibly beyond 28 days. Condensation reduced shelf life of shoots in the low-permeable materials (LDPE bag and heat-sealed PVC film) due to the accumulation of condensate in the packages, and weight loss limited the shelf life of shoots in macro-perforated LDPE bags.

6.8 Microbial load and species

Eighteen fresh bamboo shoots were sampled at CQU after harvest in Eumundi (1998) to qualitatively evaluate microbial load on surfaces of external leaf sheaths and cut ends (1.5 cm internal to the removed cut end of the shoot), and quantitatively evaluate microbial load and isolate microbial species in the internal tissues.

Both leaf sheaths and cut ends of bamboo shoots were contaminated with bacteria, fungi and coliforms (Table 21). The qualitative assessment of general bacterial, general fungal and total coliform infection at cut ends yielded significantly higher scores than on leaf sheaths.

Table 21 Qualitative microbial load assessed as aerobic plate counts (counts cm^{-2}) on surfaces of external leaf sheaths and cut ends of bamboo shoots (*B. oldhamii*)

Shoot part	General bacterial count	General mycological count	Total coliform count
Leaf sheath	10.1 ± 0.55	9.39 ± 0.546	8.61 ± 0.887
Cut end	13.8 ± 0.15	12.09 ± 0.634	12.91 ± 0.544

Quantitative figures of microbial load in the internal tissue of bamboo shoots are presented in Table 22. Several species of *Bacillus* and several genera of moulds including *Fusarium* were isolated in internal tissues. The possibility of presence of a number of different coliforms including *Escherichia coli* was indicated by the colour of colonies on Chromocult agar.

Table 22 Quantitative microbial load (cfu cm^{-2}) and microbial species isolated in the internal tissue of bamboo shoots (*B. oldhamii*)

General bacterial count	General mycological count	Total coliform count
$9.33\times10^{-2} \pm 0.212\times10^{-2}$	$4.66\times10^{-2} \pm 0.424\times10^{-2}$	$2.50\times10^{-1} \pm 0.557\times10^{-1}$
Bacterial species	Fungal species	Coliforms [a]
Bacillus sp. *B. megaterium* *B. cereus* var. *mycoides*	*Cladosporium herbarum* *Zygorhynchus* sp. *Fusarium* sp. *Trichoderma viride* *Penicillium* sp.	Salmon/red - *Citrobacter, Enterobacter*, *Klebsiella* and/or *E. coli* 0157:H7 White – other gram negative bacilli

[a] colony colour and species possibilities

The levels of microorganisms found in bamboo shoots are similar to those found on other low-growing vegetables and fruits.

6.9 Bamboo species comparison

In a comparison between *B. oldhamii* and *D. latiflorus*, shoots of *D. latiflorus* lost weight much faster than those of *B. oldhamii* (Figure 30). At the same time, respiration rate was significantly greater in *D. latiflorus* on day 0 and day 4 in storage. In this study, shoot weights of *B. oldhamii* and *D. latiflorus* averaged at 213 ± 28.9 and 626 ± 18.5 g, respectively. Due to the above-mentioned surface-to-weight relationship in bamboo shoots, conductance of thermal energy to the surface decreases with increasing size and weight of bamboo shoots. In other words, bigger bamboo shoots cannot be cooled as quickly as smaller shoots. This lag in temperature change between the interior of the shoot and the surface accelerated weight loss by respiration which accounted for more than 50 percent of total weight loss at the storage temperature of 20° C.

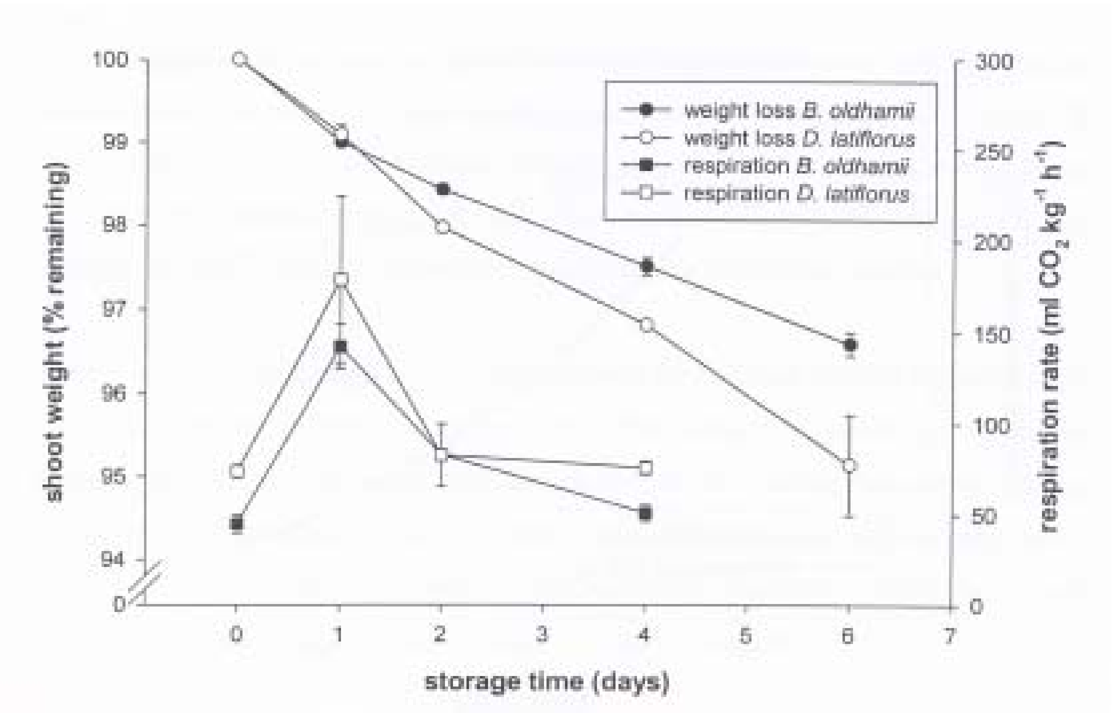

Figure 30 Weight loss and respiration in *B. oldhamii* and *D. latiflorus* shoots (packaged and stored at 20°C)

6.10 Hydrocooling

It is axiomatic that the quicker the temperature of a bamboo shoot is reduced, the longer will be its storage and shelf life. Rapid cooling or precooling particularly benefits highly perishable (eg raspberries) and/or rapidly developing (eg asparagus) horticultural crops. Compared with (standard) aircooling, hydrocooling is comparatively rapid since water has a far greater heat capacity than air. A cold water bath (tap water with food-safe ice) was tested as a simple method to cool bamboo shoots from different species. Temperature sensors connected to automatic dataloggers were used to measure the effect of hydrocooling on internal temperature of shoots.

Figure 31 shows the immediate effect of hydrocooling on internal temperature of fresh bamboo shoots (*D. latiflorus*) after harvest. Similar in weight, temperature in hydrocooled shoots decreased many times more rapidly than in those put in air within an enclosed polystyrene box on ice and the effect of hydrocooling on temperature decrease essentially depended on shoot weight (Figure 32).

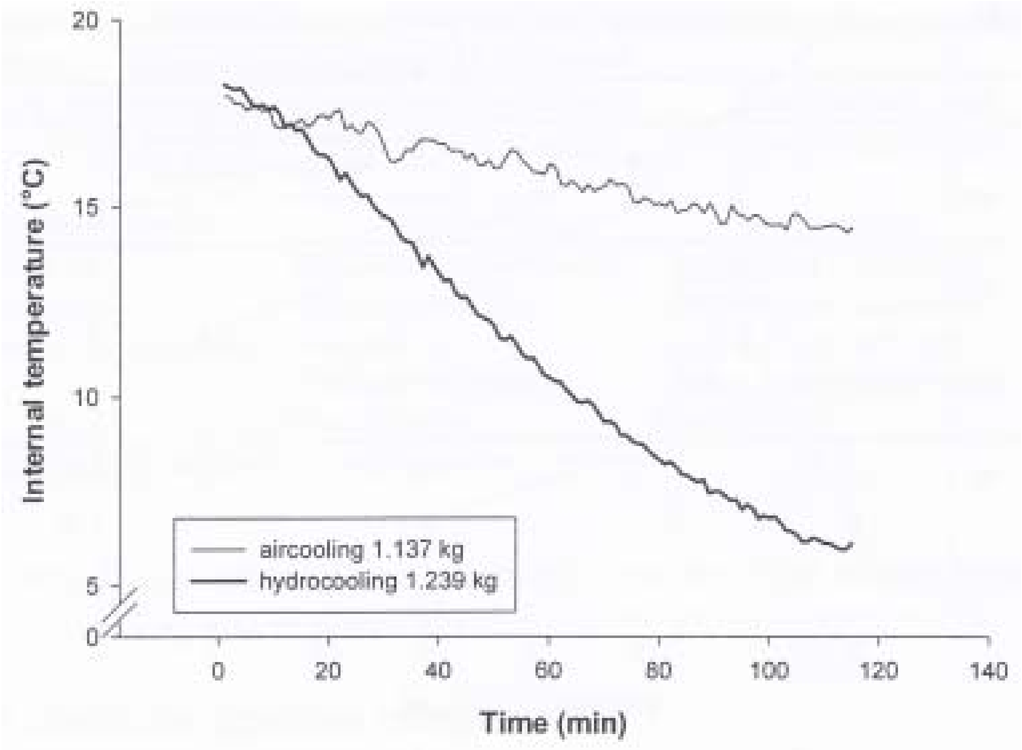

Figure 31 Effect of air- and hydrocooling on internal temperature of bamboo shoots (*D. latiflorus*)

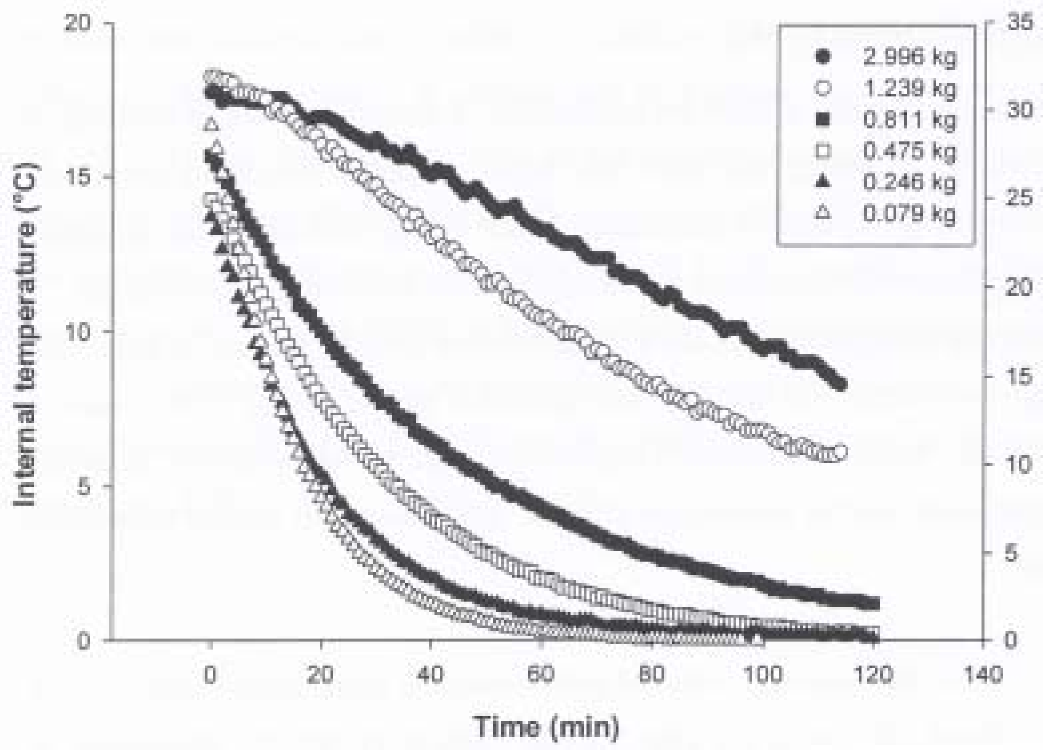

Figure 32 Decrease in internal temperature of bamboo shoots (several species as affected by shoot weight (curves are presented on different scales since initial temperature was different between shoots: left y-axis: 2.996 kg and 1.239 kg; right y-axis: all other shoots)

Internal temperature of bamboo shoots decreased exponentially with time and through non-linear regression cooling rates could be calculated for individual shoot weights. If those rates were plotted versus shoot weight (Figure 33), a relationship similar to the one between surface/weight ratio and shoot weight (Figure 24) was found. Not surprisingly, there were no differences between shoots of different species.

Figure 34 presents a preliminary recommendation for reducing internal temperature of bamboo shoots of different weight by 25°C. This would be a possible scenario for bamboo shoots harvested at an ambient temperature of 30°C during the summer season in Australia. The regression indicates that approximately 90 min hydrocooling per 1 kg shoot weight are required to reduce shoot weight to below 5°C. Collection of more data would strengthen the predictive capacity of this regression.

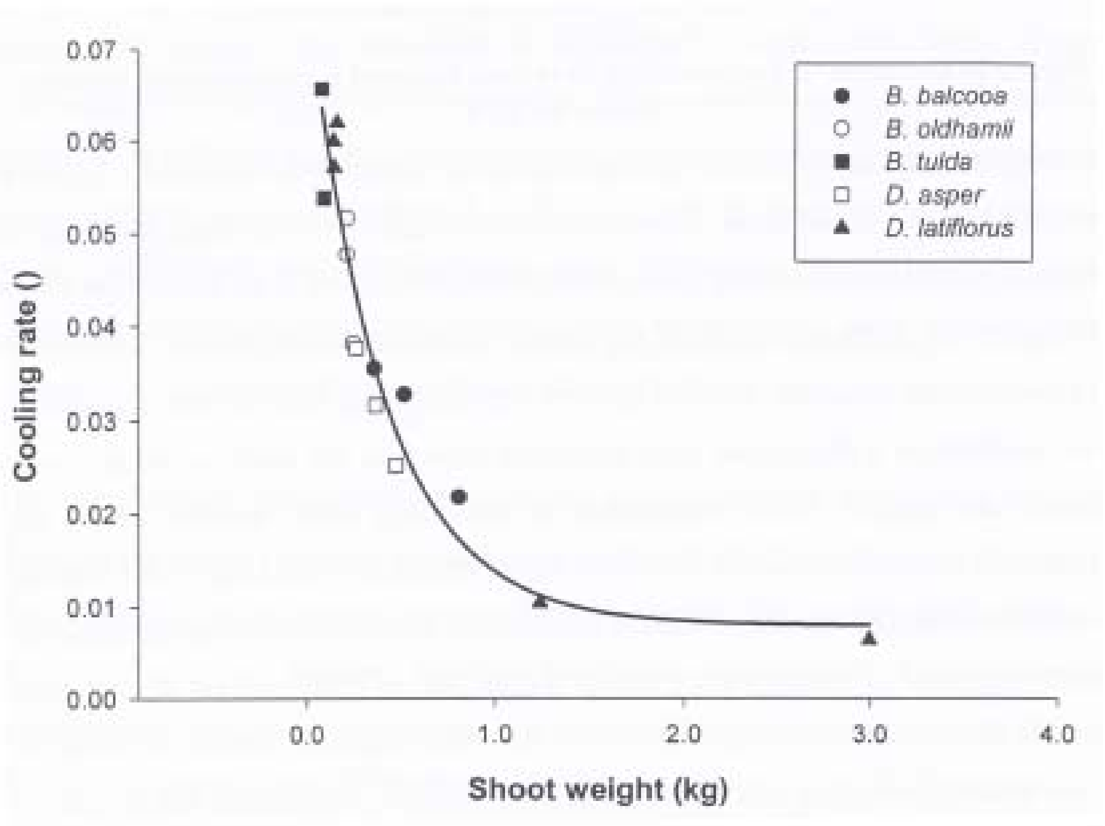

Figure 33 Cooling rate of bamboo shoots of different species as affected by shoot weight during hydrocooling

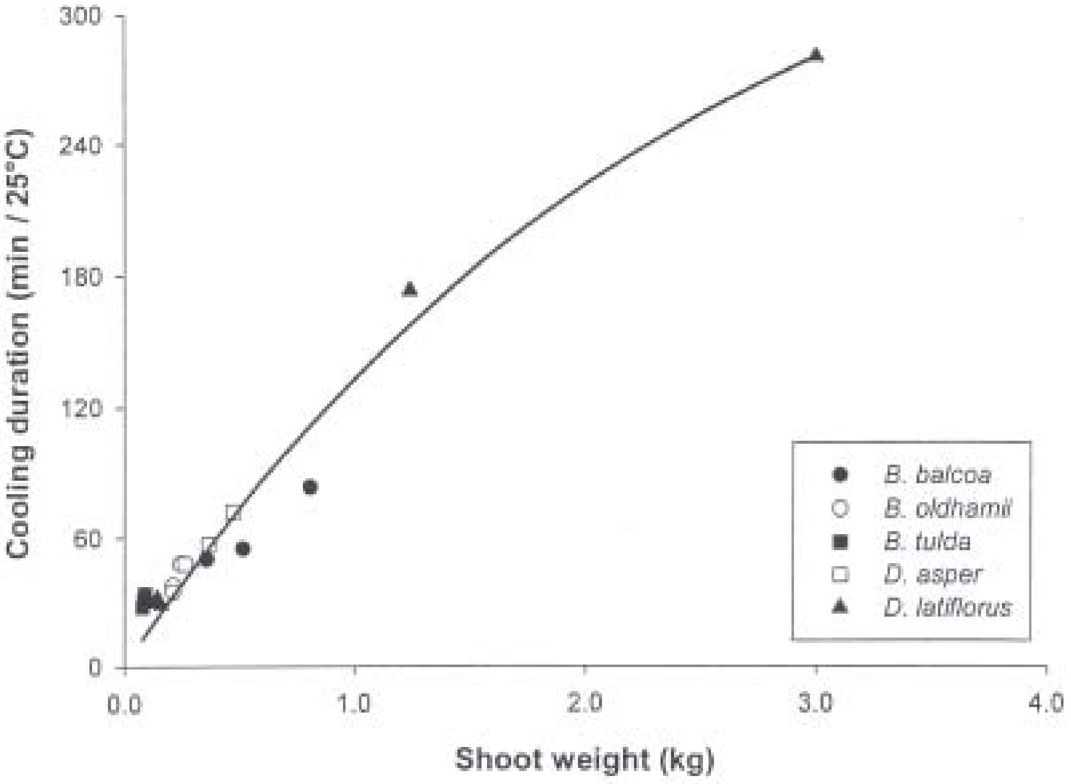

Figure 34 Duration of hydrocooling to reduce internal temperature of bamboo shoots by 25°C

In Southeast and East Asia, fresh bamboo shoots are traditionally marketed at ambient temperatures and unpackaged. When temperature cannot be controlled, shelf-life of shoots is primarily restricted by transpirational weight loss and is no longer than 1 day if measures for increasing humidity (eg baskets lined with leaves) are not undertaken. In some of those countries, bamboo growers commonly sell some of their produce on local markets on a daily basis after harvesting shoots in the early mornings. Some studies have pointed to the importance of packaging when bamboo shoots are transported from the production sites over longer distances to the larger fresh markets in urban centres. Our own observations confirm that sealed polyethylene materials are in fact beneficial to reduce transpirational weight loss in fresh bamboo shoots under ambient temperature conditions, such as on the fresh vegetable markets in Bangkok. In our studies, packaging in LDPE film at 20°C significantly reduced weight loss of bamboo shoots and extended shelf life to 6 days.

At 20°C, respiration rates of shoots averaged 94-142 ml CO_2 kg^{-1} h^{-1} at 1 day after harvest and with LDPE film, respiratory weight loss accounted for an estimated 34% of total weight loss. At this temperature, respiration peaked 1 day after harvest to decrease gradually thereafter. On this day, respiration rates were as high as those previously reported in the literature. Such high respiration rates could presumably cause fermentation under anaerobic conditions, limiting the use of vacuum packaging in bamboo shoots if they are not rapidly cooled after harvest. Although much sooner after harvest, increases in respiration have been observed in asparagus: one researcher measured an immediate increase in respiration rate of asparagus after harvest and others recorded a slight increase in respiration during the first hours following harvest. This has been attributed to rapid cell expansion in asparagus as a response to wounding. Not surprisingly, respiration in bamboo shoots was dramatically reduced by lowering the temperature to 2°C. Respiration rates of bamboo shoots at 2°C resembled the pattern of decreasing respiration rates after harvest for non-climacteric produce and respiratory weight loss of shoots with LDPE film was only 18% of total weight loss.

Reductions in storage temperature significantly reduced total weight loss of bamboo shoots with weight loss proceeding at significantly slower rates when storage temperatures were lower. Besides respiration, differences in weight loss might also be attributed to different degrees of water vapour pressure deficit of the air surrounding bamboo shoots in macro-perforated LDPE bags which decreased with increasing relative humidity at lower storage temperatures. This again emphasizes the need to quickly cool bamboo shoots after harvest. From an agronomic point of view, early harvests during the coolest time of the day should be encouraged.

The relationships between surface/weight ratio and shoot weight, and cooling rate and shoot weight clearly show that storability of bamboo shoots depends on dimensions of shoots and not on differences between bamboo species. The smaller surface/weight ratio of bigger (ie heavier) bamboo shoots is advantageous for minimising transpirational weight loss but reduces their rate of heat conductance compared to smaller (ie lighter) shoots. When shoots are stored unpackaged, weight loss caused by transpiration is many times greater than that caused by respiration which is directly related to temperature. Under such conditions, bigger bamboo shoots will loose relatively less weight than smaller bamboo shoots. However, when shoots are packaged, a much greater percentage of weight loss is caused by respiration. This explains why heavier shoots of *D. latiflorus* lost significantly more weight than smaller shoots of *B. oldhamii* (Figure 30). Those differences would have probably been smaller at lower storage temperature than the 20°C in this trial. However, the shoot weight of 626 g was much less than can be anticipated for bamboo shoots in the future in Australia. Therefore, we believe that it will be very difficult to reduce postharvest internal temperature and, therefore, respirational weight loss and microbiological activity in bamboo shoots weighing more than say 1 kg within a reasonable time frame.

When storage temperatures were kept at 8°C, bamboo shoots discoloured and were visually unacceptable after 6-10 days. Discolouration of bamboo shoots was attributed to enzymatic browning caused by phenylalanine ammonia-lyase (PAL) and peroxidase (PO), activated by tissue injury at harvest. Greater activity of PAL and PO was correlated with increase of crude fibre and lignin in shoots. In our studies, first signs of fungal growth were detected 4 days after the first brownish-black spots appeared on shoots stored at that temperature. Fungal mycelia covered those shoots almost completely after 28 days. We believe that the browning/discolouration in our experiments was primarily microbial discolouration with enzymatic discolouration being less important and/or only a secondary process.

The microbial studies revealed that bacterial, mycological and coliform microorganisms were not only present on external surfaces of bamboo shoots but also in internal tissues. It is clear that external surfaces are contaminated with microorganisms while bamboo shoots pass through the soil during growth. During harvest, microorganisms in the environment and on the harvesting tool may be drawn into the xylem, resulting in growth of rots and moulds in internal tissues. In fact, tissues contained many fungal genera (e.g. *Penicillium*) which are commonly involved in food spoilage. This may explain why the addition of a fungicide dramatically extended shelf life of bamboo shoots in one overseas study. Some authors explained increases in fibre and lignin in harvested bamboo shoots as a plant response to mechanical wounding. However, stress lignin formation in plants is also a common defence mechanism to pathogen attack. In mature bamboo culms, fungal rot (white, brown and soft rot) was greater in cell walls of fibres with low lignin contact and young culms were more susceptible than mature culms. Although the mycological genera involved were different to those identified by us, the implications could be similar for fresh bamboo shoots as they are themselves immature culms.

We have isolated microorganisms which can be potentially hazardous for human health (eg *Bacillus*, *Fusarium*, and possibly *E. coli* and other members of the *Enterobacteriaceae*), some of which are common in the environment and ingested in many foods. However, we are not able to judge whether the microbial load that was measured in fresh bamboo shoots is great enough to be a concern when assessing food safety issues, given the present lack of food safety standards. It is unlikely to be worse than for other vegetables with exposed cut surface and edible parts close to the soil surface (e.g. asparagus), many of which are eaten raw (eg lettuce).

Further reduction in storage temperature essentially eliminated discolouration and fungal growth in bamboo shoots. On shoots stored at 1°C, only a few yellow stains developed and no fungal growth was visible after 28 days. At this low storage temperature, the choice of packaging material is another option to improve postharvest quality and extend shelf life in bamboo shoots. Perforation had a significant effect on weight loss through the materials and on total weight loss. Shoots in the macro-perforated LDPE bags lost nearly twice the percentage of weight than did the micro-perforated LDPE bags. Most of this loss was through the packaging material as indicated by the low indices of internal/external weight loss and this reduced shelf life to 17 days. In contrast, condensation within materials reduced visual quality of packages when low-permeable LDPE bags and heat-sealed PVC film was used. Although total weight loss of bamboo shoots in those materials was not different from the micro-perforated LDPE bags and LDPE film, there was a great difference in the ratio between internal and external weight loss between those and all other materials. Although only significant for the heat-sealed PVC film, more weight in those materials was lost within packages as indicated by high ratios. This was manifested in accumulation of condensation water within packages. We did not test bulk packaging of bamboo shoots but for packaging of individual bamboo shoots in LDPE bags and heat-sealed PVC film, condensation within bags would have reduced visual acceptability of packages to 21 and 14 days, respectively.

Condensation water can act as a growth media for microorganisms in horticultural produce but we did not observe differences in discolouration and fungal growth between packaging materials. Apart from their low permeability to water vapour transfer, film thickness might have played a significant role in triggering condensation in the low-permeable materials. After harvest, bamboo shoots contained 93.0 ± 0.25% water and although we did not measure transpiration coefficients, we expect these to be rather high compared with other (bulky) horticultural produce. Even small fluctuations in temperature can decrease the temperature of the humid air in packages below its dew-point temperature and consequently, water vapour condenses. In contrast to the voluminous bamboo shoots, the packaging materials have much greater heat conductivity, ie their temperature changes relatively quickly with changes in air temperature. Although only statistically significant for the heat-sealed PVC material, small changes in storage temperature apparently caused significant condensation of water vapour on the inner surface of the low-permeable materials when their temperature decreased below the dew point temperature of the air inside packages. Condensation was much greater in heat-sealed PVC film than in LDPE bags. This may be attributed to film thickness which was greater for the PVC film (90 μm). It could be argued that due to greater film thickness and therefore lower flexibility of the material, the PVC material was to a lesser degree in intimate contact with bamboo shoots and, consequently, there were greater temperature fluctuations which accelerated condensation. It follows that under low storage temperature, thin packaging material should be used. Bags should be of a size to fit bamboo shoots snugly, to bring the material in intimate contact with the produce.

The most suitable packaging materials in our studies were the thin, micro-perforated (45µm, 0.01% perforation) LDPE bags and the non-perforated but probably imperfectly sealed LDPE film (10.5µm thick). These materials reduced total weight loss of shoots to about 5% after 28 days, minimised condensation within packages and extended shelf life of bamboo shoots to and probably beyond 28 days. This was true for bamboo shoots at a weight of 148 ± 8.6 g shoot^{-1} that could be rapidly cooled after harvest. It would take about 10 h to cool a 1-kg bamboo shoot from 30 to 1°C in aircooling and 2.5 h in hydrocooling. For a 3-kg bamboo shoot in hydrocooling this duration would extend to 6 h in hydrocooling and possibly 1 day when aircooled. This may indicate that without hydrocooling or more advanced rapid cooling methods, shelf life of bamboo shoots of big size may not be longer than one or two weeks.

Box 5: Cooling of shoots and storage

Storage losses from harvested shoots through transpiration (loss of water), respiration (biochemical breakdown of carbohydrates) and discolouration/fungal infection, should be minimised by the grower/retailer during the harvest, grading transport and display of product.

Both the cut surface of the shoot and the sheaths of the shoot lost similar amounts of water (20% of total weight by each over 28 days of storage) hence some physical protection is necessary to reduce this. Increasing storage temperature also led to greater weight loss; a 5% weight loss (considered the maximum allowable for marketable produce) was evident after 1 day at 25ºC, 5 days at 11ºC, 10 days at 8ºC and 17 days at 1ºC. Hydrocooling (in icy water) was very effective at getting shoot internal temperature down to less than 5ºC; the smaller the shoot the quicker this temperature was reached. On average, c. 120 minutes were required for shoots <1.0 kg.

Visually, shoots stored at 8ºC declined in quality after 6 days of storage, while at 1ºC there was no notable discolouration even after one months storage. Some of the discolouration was due to growth of bacteria and fungi, but the species represented on shoots were similar to those found in the soils (contamination most likely occurred during harvest of shoots) and on other vegetables harvested near the soil surface (eg lettuce, asparagus).

Overall, to minimise weight loss and discolouration, storage of hydro-cooled shoots at c. 1ºC in thin, micro perforated low-density polyethylene bags (45 mm, 0.01% perforation) reduced weight loss of shoots to an acceptable 5% after 28 days storage, with negligible discolouration and fungal growth.

Implications and Recommendations

The data collected with this project go a long way to satisfying the demand by the industry for sound production and post-harvest management procedures.

The need for sustained water supply just prior to and through the shoot system, maintenance of total leaf nitrogen at *c*. 3.0%, and the establishment of c. 9 culms per clump (in *B. oldhamii*) with emphasis on relatively more younger than older culms, are highlighted.

Packaging of shoots in semi-permeable materials and storage at a 1°C ensured shelf life of 28 days, without significant weight loss or discolouration, although the ACBC have recommended 2ºC due to specification of transport systems, and this temperature likely to be equally effective.

The establishment of the Australian Commercial Bamboo Corporation has hopefully brought most bamboo growers together, and they as a group and other non-members can capitalise on these findings.

Further research is required on the potential benefits of: -

Fertigation

Maintenance of all culms at <3 years of age (for shoot and pulp)

Within population variability in vigour and shoot quality

Shoot size, as it is becoming a market issue with clients often prefering smaller rather than larger shoots, and light in colour.

Marker-assisted selection for shoot and culm qualities

Rapid, cheap production of planting materials to supply the timber industry

Comparison of timber qualities, wall thickness and strength

Measuring the cyanide content and the rate of dissipation of cyanide after harvest, after grating raw, and after chipping raw.

Cooperation with overseas research institutes.

Some of these activities are currently underway at CQU.

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