Curtin University of Technology
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Bioconversion of waste paper by termites: A landfill of opportunity

A feasibility study of employing Australian subterranean termites in the management of discarded paper (lignocellulosic waste).

November 2006

This dissertation is submitted in partial fulfilment of the requirements for the degree of Honours in the Bachelor of Science (Environmental Biology) at Curtin University of Technology. It represents 85% of the formal course requirements for one academic year.

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Abstract

Termites (order Isoptera) are insects, with a highly evolved social system of soldiers, workers, and two reproductive classes. Australia houses more than three hundred species, and colonies can have a million or more members, with prolific egg production from queens.

Waste paper is in large supply in landfills and increasing daily. Since termites obtain most of their energy requirements from the digestion of cellulose, there is an opportunity to utilise their services to break down this waste paper and utilise the resulting termite biomass as a food source for the aquaculture, pig, and poultry industries. Nutrients left behind in termite wastes may also be useful for horticultural purposes, particularly compost.

The aim of this project was to look at the feasibility of this idea, with emphasis on applications in areas where recycling is not economically feasible, as recommended by the Desert Knowledge Cooperative Research Centre centred in Alice Springs, Northern Territory.

This project commenced with a pilot study in Perth, using a colony of *Coptotermes acinaciformes* in a termitarium. Here, the attractiveness to termites of different types of waste paper was evaluated. *C. acinaciformes* decomposed a total of 5.9 kg of paper over 20 weeks, displaying a preference for newspaper over glossy-coated paper, and glossy paper over bleached office paper. Trial two involved mixing paper types and adding moisture, which increased overall decomposition, but saturated samples were less preferred. The termites decomposed 6.9 kg of paper over 20 weeks.

The decomposed remains and soil in the laboratory containers were evaluated for nutrients of horticultural significance via two pot trials and CSBP analyses. Mixing termite workings into a sand and peat control (4:3:1) increased the pH from 4.96 to 8.18 and conductivity from 0.08 to 0.25 dS/m. The workings mix revealed low levels of nitrogen and high levels of phosphorus, potassium, sulphur, organic carbon, and the trace elements copper, zinc, manganese, and iron. Addition of nitrogen to the workings increased plant productivity substantially.

Then, next to the landfill of the Alice Springs rubbish tip, the trial was extended to a large-scale field evaluation, using 44-gallon drum feeding stations exposed to *C. acinaciformis*. The feeding stations were successful in focusing feeding activity, but decomposition of the paper in the plastic bags was relatively low. The most successful bag showed 561.6 g decomposed paper (20.8 %) over 20 weeks.

Acknowledgements

My thanks and gratitude extend to my supervisor, Jonathan Majer, for his invaluable contribution of time and assistance throughout this project.

Secondly, to the Desert Knowledge Cooperative Research Centre, based in Alice Springs, for funding the project and allowing me to attend the conference and symposium.

I would also like to thank:

- TMA Corporation and Bowerbird Enterprises Pty Ltd for the use of their facilities in Perth and Alice Springs, respectively.
- Western Recycling Pty Ltd for their contribution of waste paper.
- The technical staff within the Department of Environmental Biology, particularly Peter Mioduszewski for help with the pot trial supplies.
- Melinda Hillary for expertise and help in prospecting for and identifying termites in Alice Springs.
- Katie Chatto from the Alice Springs Desert Park for transport and discussions.
- John Llewelyn from the Bowerbird Tip Shop for watering my feeding stations.
- Mick Café for help and transport of materials during my stays in Alice Springs.
- Brian Leach for agronomical advice on the soil analyses and pot trials.
- John French for advice and contribution of the termite feeding station model.
- Shenton Surin for help with harvesting of pot trials and proof-reading.

Finally, I thank my family and friends for their support throughout the past two years.

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1.0 Introduction

1.1 Biology of termites

Termites (order Isoptera) are insects which have a highly evolved social system of soldiers, workers, and two reproductive classes (Hadlington, 1987). They are found predominantly in the tropical regions of the world (Krishna & Weesner, 1969; Gullan & Cranston, 2000; Pearce, 1997). The morphological forms, or castes, exhibit division of labour and perform different biological functions for the maintenance and survival of the colony (Krishna & Weesner, 1969; Hadlington, 1987). A colony can vary from about 100 to millions of individuals (Hadlington, 1987; Andersen & Jacklyn, 1993).

The king and queen are the once-winged reproductives (alates), originating from the dispersal flight of the parent colony (Krishna & Weesner, 1969; Hadlington, 1987). The alates find substrate with appropriate conditions to nest and establish, lose their wings, and reproduce (Krishna & Weesner, 1969; Hadlington, 1987). They feed and care for the young until there are sufficient soldiers and workers to take over the duties of the colony (Krishna & Weesner, 1969; Hadlington, 1987).

Termites are structurally most closely related to cockroaches (Krishna & Weesner, 1969; Pearce, 1997). Though similar in eusociality, they differ from ants, bees, and wasps (order Hymenoptera) in that they are hemimetabolous and castes are usually bisexual, involve immature stages, and have no known subsocial groups (Krishna & Weesner, 1969; Gullan & Cranston, 2000).

Termites obtain most of their energy requirements from the digestion of cellulose in dead grass, wood, and other plant material (Andersen & Jacklyn, 1993; Pearce, 1997). They are perhaps most recognised by the damage they cause to timber and buildings (Creffield, 1996; Hadlington, 1987). The inability of most insects to digest cellulose is well documented and, among the few insects capable of cellulose digestion, termites (through their symbionts) are more efficient than the wood-boring beetles and siricid wood wasps (Martin, 1983). Cellulose is the most abundant renewable biomass in nature, and

termites are considered one of the major cellulose-decomposing animal groups (Tokuda *et al.*, 2004).

Breakdown of the predominantly crystalline cellulose matrix requires a cellulase enzyme complex (Martin, 1983). These enzymes are provided to termites via symbiotic organisms; the organisms involved and where they dwell have led researchers to classify termites into higher and lower forms (Martin, 1983; Tokuda *et al.*, 2004). The higher termites (family Termitidae), which comprise about 75% of all termite species, lack the symbiotic protozoa found in the hindgut of lower termites, are more associated with symbiotic bacteria, and have a more elaborate and rigid caste system (Krishna & Weesner, 1969; Gullan & Cranston, 2000; Tokuda *et al.*, 2004). Lower termites exhibit little or no distension of the queen's abdomen, and enzymes are secreted by symbiotic protozoa which contribute to the breakdown of gut contents (Krishna & Weesner, 1969; Gullan & Cranston, 2000).

Due to the variability of behaviours, habits, and nesting types within the order Isoptera, and the usefulness of this in species identification, termites are also often grouped into categories such as dampwood, drywood, tree-dwelling, and subterranean species (Verkerk, 1990; Creffield, 1996). Subterranean termites may be defined as those species requiring contact with the soil or a continuous moisture supply (Verkerk, 1990). It is the subterranean termite that causes the greatest amount of damage to timber and buildings in Australia, and this concern has been one of the main drivers for research into this group of termites (Verkerk, 1990; Creffield, 1996).

Two of the subterranean species recognised in Australia are *Mastotermes darwiniensis* Froggatt (Isoptera: Mastotermitidae) and *Coptotermes acinaciformes* Froggatt (Isoptera: Rhinotermitidae) (Krishna & Weesner, 1969). *M. darwiniensis* and *C. acinaciformes* are Australia's most destructive and economically important termites respectively, and are distinguished by their ability to consume most wood types (Haritos *et al*., 1994; Creffield, 1996; Andersen & Jacklyn, 1993).

M. darwiniensis (the Giant Northern Termite) is a tropical species that occurs in northern Australia, with its southern limit of distribution approximating to the Tropic of

Capricorn (Creffield, 1996). Apart from its diet of wood, *M. darwiniensis* is known to attack almost anything, including electric cables, leather, wool, bitumen, rubber, lead and even ivory billiard balls (Andersen & Jacklyn, 1993; Creffield, 1996). *M. darwiniensis* is a large endemic species, with soldiers averaging 11.5-13.0 mm in length (Creffield, 1996).

C. acinaciformes occurs throughout most of Australia and is recognised for its tree-piping ability and as one of the few species that attack living trees as well as dead plant material (Andersen & Jacklyn, 1993). This species is often grouped along with *Coptotermes frenchii* and *Coptotermes lacteus*, because of their similar habit and the difficulty in distinguishing between them (Creffield, 1996). The soldiers of this species average 6 mm in length (Creffield, 1996).

1.2 Paper, a lignocellulosic waste

Paper is lignocellulosic in nature, and mainly composed of a mixture of cellulose (ca. 40%), hemicellulose (ca. 20-30%), and lignin (ca. 20-30%) (Sjostrom, 1993 as cited in Tuomela *et al*., 1999). It was initially made from vegetable fibres in China about two thousand years ago (Lund, 2001). The first paper-making machine was invented in 1799 and, by 1850, wood fibre began to replace agricultural fibres (Lund, 2001). Today, a large amount of paper and board is made from the residuals of lumber production, namely trimmings, shavings, and sawdust (Lund, 2001). Some paper is produced from wood specifically grown for pulp (Lund, 2001).

Waste is a by-product of human activity which is considered to lack value or use (Datta, 1997). Lignocellulosic waste, as paper, comprises a large portion of the world's solid waste; management of this material is costly.

Solid waste management entails a number of practices which aim at minimising the quantity of waste produced, as well as disposing of remaining waste (Datta, 1997). Waste may be reduced at the source through proper design and manufacture, and by producing long-life and long-use materials (Datta, 1997). Non-recyclable, unusable, or non-economic waste is disposed of in landfills, prior to which it may undergo transformation such as by shredding, compacting, and encapsulation to reduce the land area required (Datta, 1997).

A more recent and environmentally sound approach to solid waste management involves recovery of resources through waste processing or recycling (Tuomela *et al.*, 1999; Datta, 1997). This involves physical, chemical, or biological alterations of wastes to recover conversion products for re-use (Datta, 1997). Recyclable materials can find a ready market if they have a high value relative to the costs of collecting and reprocessing them (I.C., 1991). Recycling is not economically feasible where there are technical constraints, or where production of virgin materials is less costly (I.C., 1991).

Recycling of fibre in the paper manufacturing industry is well established in Australia (ACOR, 2002), with major recycling centres being in Sydney, Melbourne, Brisbane, and Perth (I.C., 1991). More than 1.6 million tonnes were used in domestic production in 2000-01 (ACOR, 2002). Major recycling centres around the world have expanded in response to higher costs of new landfill sites and tighter environmental requirements (I.C., 1991). These factors contribute to the diversion from landfill to resource recovery through recycling (I.C., 1991).

The paper recycling industry does not feasibly function everywhere, and there are a number of restrictions and limitations where it does. The bulk of recyclables come from industrial sources, where collection costs are low and waste material is of high quality (i.e. homogeneous and clean) (I.C., 1991). Other sources of recyclable lignocellulosic waste must undergo a costly process of collection, transport, storage, sorting, treatment, etc. (Clark, 1978; Datta, 1997; I.C., 1991). This creates a gap between industrial and household quality waste-paper and marginalises non-recyclable material to landfill.

Retrieved waste paper for recycling must also abide by national and, if applicable, international specifications to reach end-use quality. In Australia, these are found in the Australian Recovered Paper Specifications (AuRPS), as published by the Australian Council of Recyclers (ACOR, 2002). Supplies of paper are sorted into fifteen grades which are restricted by moisture and material such as adhesives, coatings, inks, treatment chemicals, and varying amounts of ‘prohibitive materials’ (such as plastic, glass, metal, timber, dirt, food, high-wet-strength papers, and waxed boxes) (ACOR, 2002). Paper quality can be restricted to such levels as that of the hard white ledger grade (AuRPS

HWL-31), which requires no more than 0.15% of these prohibitive materials in the overall supply (ACOR, 2002).

These factors have led researchers to seek more innovative ways of managing lignocellulosic waste to divert the road to landfill and to recover conversion products for re-use. One model for waste treatment is the integration of sustainable biological systems. This idea has been applied to urban wastewater management by integrating engineered artificial wetlands with algae and macrophytes to filter nutrients before it flows into a natural wetland or river (Environmental Directory, 1999). A sustainable biological system is set up, the waste is transformed via natural processes, and nutrients are placed back into the nutrient cycle. The question here is 'could this model be applied to lignocellulosic waste via a system of subterranean termite colonies, lending to useful conversion products through resource recovery?'

Waste is a foreign concept to a natural ecosystem, because wastes produced by a species become inputs for others in the same ecological system. This biological concept has been applied to industrial structures and is termed Industrial Ecology (IE) (Pento, 1999). IE aims to similate natural ecosystems so that the system (i.e. paper industry) takes less materials and energy inputs from the natural environment and smaller amounts of waste are re-deposited into the environment (Pento, 1999). More comprehensive IE procedures in the paper industry are mainly driven by legislative measures, and one development route is the recognition of, and research into, the fact that the products of the industry are returned to the carbon cycle of the natural environment (Pento, 1999).

Millions of tonnes of materials in Australia continue to be disposed of in landfill, despite gains in resource recovery (Warnken, 2005). This accounts for the majority of waste produced in Australia (Warnken, 2005). In order to take resource recovery to the next level, Warnken (2005) explains that there needs to be a drive toward investment in resource recovery infrastructure, a transfer of the cost of end-of-life management services directly to the consumer and producer, and provision of a financial reward for the value of services provided by the resource recovery sector.

1.3 Termites as decomposers of lignocellulosic waste

Waste paper differs from natural food sources of the termite in that paper and printing inks contain trace levels of toxic xenobiotics, particularly polychlorinated biphenyls (PCB's) (Haritos *et al.*, 1993). Their lipophilic nature and resistance to degradation results in PCB's being deposited and concentrated in fatty tissues of organisms which are unable to metabolise and excrete them (Haritos *et al.*, 1993). Two multicomponent enzyme systems responsible for metabolism of a broad range of foreign and endogenous chemicals are cytochrome *P*450 monooxygenases (E.C. 1.14.14.1) and glutathione *S*-transferases (GST's, E.C. 2.5.1.18) (Haritos *et al.*, 1994). These enzymes convert lipophilic chemicals into water-soluble products that are readily excreted (Haritos *et al.*, 1994).

Haritos *et al.* (1993) found that both *C. acinaciformes* and *M. darwiniensis* metabolised and eliminated lipophilic xenobiotics in treated waste paper; this was particularly pronounced with *M. darwiniensis*, which they propose as a potential candidate for biogenic conversion of waste paper. Monooxygenase activities were tested using the substrates aldrin, 7-ethoxyresorufin, and 7-ethoxycoumarin. Compared with other insects, aldrin epoxidase (AE) activity was low, 7-ethoxyresorufin *O*-deethylase (EROD) activity was similar, and 7-ethoxycoumarin *O*-deethylase (ECOD) activity was high in both termite species, but especially so in *M. darwiniensis* (Haritos *et al.*, 1994). In fact, although termites are reported to exhibit avoidance behaviour to pesticides rather than the development of resistance (Lockwood *et al.*, 1984 as cited in Haritos *et al.*, 1994), the two species exhibited ECOD activity similar to pesticide resistant strains of insects (Haritos *et al.*, 1994). This ability to metabolise lipophilic xenobiotics in waste paper gives credence to *C. acinaciformes*, and particularly *M. darwiniensis*, as potential candidates for the biogenic conversion of wastepaper.

1.4 Objectives

Australian subterranean termites have the potential to be employed in the management of lignocellulosic waste (i.e. discarded paper), leading to nutrient-rich compost being available for horticultural purposes and termite biomass being a source of protein for the aquaculture, agriculture, and other animal-rearing industries. This project aims to look at

the feasibility of this idea, with emphasis on applications in areas where recycling is not economically feasible, as recommended by the Cooperative Research Centre for Desert Knowledge, centred in Alice Springs, Northern Territory.

The Alice Springs Landfill Management Plan predicts the landfill of Alice Springs to reach full capacity between 2020 and 2030 (ASTC, 2003). A partnership between the Alice Springs Town Council and Bowerbird Enterprises Pty Ltd (an initiative of the Arid Lands Environment Centre) aims to reduce the amount of waste going to landfill and increase the amount of recycling in Alice Springs (ASTC, 2001). In terms of waste recycling, the Alice Springs Organic Recycling Centre has been processing tonnes of green waste since 2002. There is, however, no significant paper recycling in Alice Springs at present, and there are limited nutrient-rich materials available locally to mix with paper for composting.

Initiatives by the Alice Springs Town Council have promoted environmental sustainability and the preservation of the natural environment, including the reduction of waste going to the landfill (ASTC, 2004). The project should result in a viable means for reducing the amount of waste paper that normally ends up in landfill and other waste disposal areas. It should also provide a fat- and protein-rich source of food for the aquaculture, pig, or poultry industries. The resulting technology could result in the establishment of a series of small cottage industries.

2.0 Materials and methods

This project commenced with a pilot study in Perth, using a colony of *Coptotermes acinaciformis* in a termitarium. The attractiveness to termites of different types of waste paper encased in 3-litre plastic containers was evaluated in trial 1, and a mixture of paper types with different moisture levels in trial 2. The decomposed remains and soil in the laboratory containers were evaluated for nutrient content via two pot trials and CSBP nutrient analyses. Then, next to the landfill of the Alice Springs rubbish tip, the trial was extended to a large-scale field evaluation, using 44-gallon drum feeding stations exposed to *C. acinaciformis* and other local species.

2.1 Laboratory trials

Trials were conducted in a privately owned termitarium in Perth, Western Australia which houses a captive colony of *C. acinaciformes* (Figure 1). It was a concealed termitarium with controlled lighting, temperature, humidity, and water supply. The temperature was controlled by a thermostatic heater. Humidity was maintained at a high level by a fan blowing on a bath towel 'wick' hanging out of a water bath. The structure consisted of three soil beds (each about 1 metre x 1 metre x 1 metre) connected to the parent mound via a series of poly-pipes. Similar laboratory infrastructure and required environmental conditions for rearing termites have been described by Krishna and Weesner (1969).

Figure 1. Termitarium containing three soil beds and the parent mound.

2.1.1 Termitarium Trial #1

Three types of waste paper were used: newspaper, 'white' office paper, and 'glossy' magazine-type paper. Each paper type was rolled up, weighed, and placed in a transparent plastic container (about 3 litre) with six holes drilled in the bottom for termite access (Figure 2). Each paper treatment was replicated 10 times.

Figure 2. Three paper treatments in plastic jars (glossy paper, office paper, and newspaper) (left) with holes drilled in the bottom for termite access (right).

The containers were placed out in one of the three soil beds in the termitarium, alternating clockwise from one corner (as shown in Figures 1 & 3) to obtain random distribution. This catered for bias such as distance from the four limestone water wicks, from each other, and from the poly-pipe access route to and from the mound (i.e. the housed queen). Termite activity and decomposition was observed over time, and it was decided that enough data of decomposition would be obtained after 20 weeks. The samples remained in the soil bed from 9 May – 8 Oct., 2005.

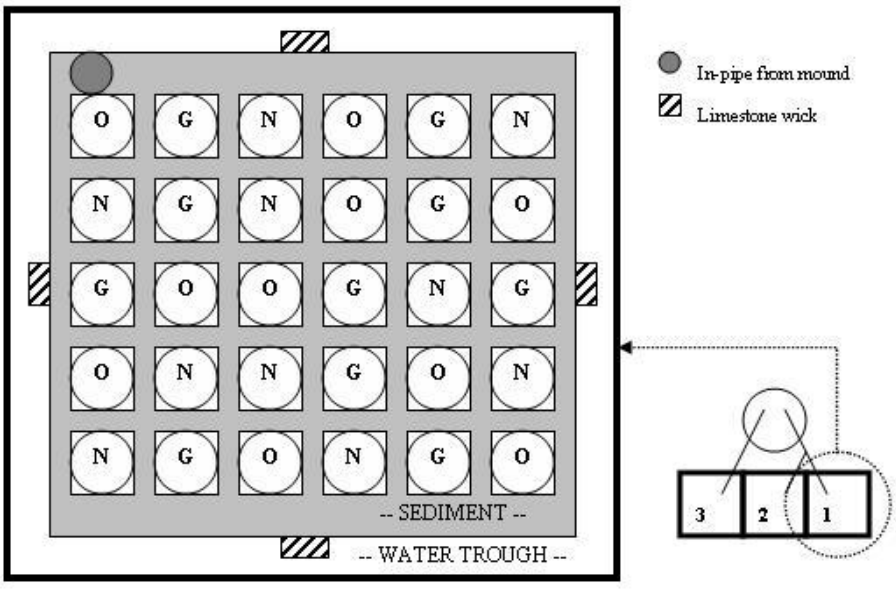

Figure 3. Layout of the paper preference trial, showing arrangement of samples of three paper types (N – newspaper, O – office paper, G – glossy paper) in transparent plastic containers in the termitarium.

Intact paper was separated from the workings (which included paper fragments, castings, and soil brought up by the termites) and each was weighed separately (Figure 4). This was more difficult in the office and glossy paper treatments than the newspaper, as some material was stuck to the paper (including faecal pellets).

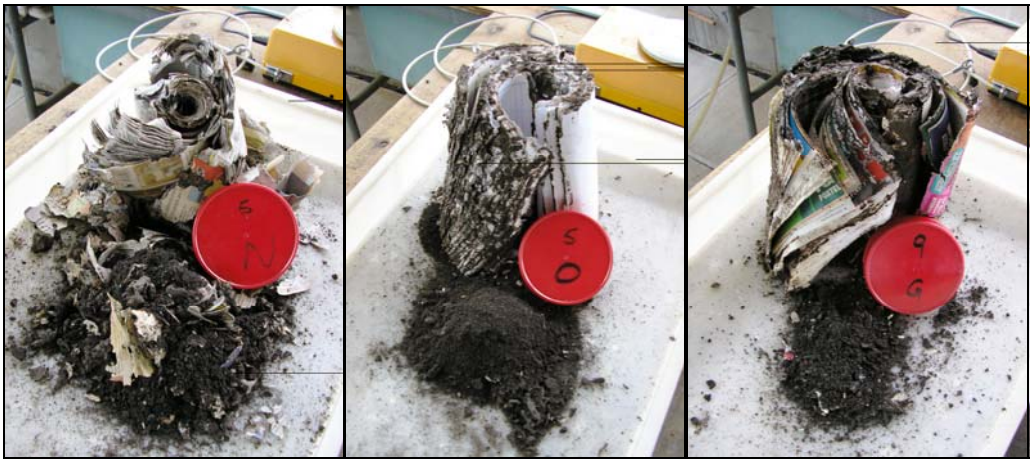

Figure 4. Separating intact paper from the workings within the harvested newspaper, office paper, and glossy paper samples (from left to right).

To account for the water within the treatments, three samples of the original paper for each paper type were placed in a 60°C oven for 4 days and reweighed. The mean percent dry weights were applied to the data to calculate dry weights and moisture percentages. This procedure was also done (taking one sub-sample) for the harvested intact paper and the separated workings for each of the samples to calculate dry weights. This was done because of the large amount of the material and a lack of oven space. Data were analysed using one-way ANOVA and the Scheffé test to test the null hypothesis that there was no significant difference in decomposition between the paper types.

2.1.2 Termitarium Trial #2

The aim of this trial was to look at the effect of adding moisture to the paper before exposure to termites and to look at the effect of mixing paper types. The methods and materials for this trial were the same as in Termitarium Trial #1 except that the treatments being tested in the termitarium bed and the number of replicates differed.

Three types of paper samples were used: glossy paper (as in Termitarium Trial #1), a glossy/newspaper combination (1:1) mixed together, and a glossy/newspaper combination saturated with water. The latter samples were weighed prior to saturation to allow for a correction for moisture using dehydrated sub-samples. The glossy paper and newspaper were mixed by alternating four sheets of paper on top of each other. Each treatment was replicated five times. The trial was left for 20 weeks as in Trial #1 (28 Oct. – 30 Mar., 2006)

Analysis of harvested samples was the same as in Termitarium Trial #1 and results were analysed using one-way ANOVA and the Scheffé test.

2.2 Analysis of termite workings

2.2.1 Pot Trial #1 using *P. hybrida*

The aim of this trial was to look at the effect of termite workings mixed with soil on the growth of the nutrient-sensitive *Petunia hybrida*, and thus reveal any nutrients of horticultural significance. The trial was conducted in a shaded glasshouse using *P. hybrida* seedlings (‘dreams red’ variety). Four soil treatments were prepared and placed in plastic 1-litre pots with 10 replicates for each treatment (see Table 1). The initial height and number of leaves of each seedling were documented. The plants were watered three times per week over a period of 4 weeks. Thrive® soluble all purpose plant food was prepared in a watering can according to the manufacturer’s directions and applied to the fertiliser treatments at the beginning of each week (see Table 2).

TABLE 1. Four treatment levels of soil preparations applied to *P. hybrida* seedlings. The composition of the Thrive® fertilizer is shown in Table 2.

Treatments	**Soil composition**
Control mix (C)	Riversand + peat [3:1]
Paper (P)	Riversand + peat + **ground newspaper** [3:1:4]
Workings (W)	Riversand + peat + **workings** [3:1:4]
Fertiliser (F)	Riversand + peat [3:1] + **Thrive®** soluble all purpose fertiliser

TABLE 2. Nutrient content of eight grams of Thrive® soluble all purpose fertiliser in 4.5 L of water, as calculated from nutrient percentages on the packet and as recommended by the manufacturer.

Nutrient	(mg)
N as Nitrate	240
N as Ammonium	208
N as Urea	1712
Total N	2160
Total P (water soluble)	440
Total K as Nitrate	720
S as Sulphate	17.6
Fe as Chelated Iron	14.4
Mg as Sulphate	40
Mn as Sulphate	3.2
Zn as Sulphate	1.6
B as Sodium Borate	0.4
Cu as Sulphate	0.4
Mo as Sodium Molybdate	0.16

One preparation of Thrive® was used over the four weeks (8 grams per 4.5 litres of water). Temperatures ranged from 15-41°C over the trial period (16 Nov.-17 Dec., 2005). After this period, the number of leaves and flowers were counted and height measured. The soil was carefully separated from the roots of each plant and washed in a water bath. The plants were placed in paper bags and allowed to dehydrate in a 60ºC oven for 4 days. The samples were then weighed to obtain dry weight. Results were analysed using one-way ANOVA and the Scheffé test to test the null hypothesis that there were no significant differences between the means of the four plant productivity factors for each treatment.

2.2.2 Nutrient analysis

The aim of this CSBP nutrient analysis was to measure total and available nutrient contents of the plant and soil material, respectively, of the first pot trial, which could then be used for comparison and to look for growth-limiting factors and to quantify available nutrients. The paper and workings for each paper type and the termitarium soil bed were then analysed for total and available nutrients, respectively, to trace the source of the nutrients found.

2.2.2.1 Soil analysis of available nutrients

The four soil treatments of the first pot trial were prepared again and placed in 1-Litre jars (5 replicates). Five soil samples were taken randomly from the trial bed in the termitarium to compare with the workings mix. These were analysed as a soil medium at CSBP for available nutrients.

2.2.2.2 Plant analysis of total nutrients

The dry plant material from the first pot trial was ground and placed in vials for each of the four soil treatments (5 replicates). The samples were analysed for total nutrients at CSBP to see how much of the nutrients were drawn from the soil treatments.

2.2.2.3 Paper and workings analysis of total nutrients

Newspaper, office paper, and glossy paper as in Termitarium Trial #1 were individually ground and placed in vials (5 replicates). The same was done for termite workings (including soil, castings, and paper fragments) from the first termitarium trial for each paper type. The vials were taken to CSBP and analysed for total nutrients.

2.2.3 Pot Trial #2 using *P. hybrida*

This trial was done after and accordance to the CSBP nutrient analysis of the soil treatments and dry plant material from Pot Trial #1. The aim of the trial was to see if nitrogen was the main limiting nutrient in the growth of *P. hybrida* in the workings mix, and to see if the phosphorus and potassium content shown in the CSBP results were available to the plants when given sufficient nitrogen. Trace elements were not included as a variable in the trial, as results showed sufficient levels in the soil treatments and the plant material from the previous trial.

The methods and materials employed in the trial were the same as Pot Trial #1, except that the soil treatments being tested and the number of replicates differed. The control,

workings, and fertilizer treatments were the same as for the previous trial. A 'workings' treatment with urea was added in place of the paper treatment (Table 3).

TABLE 3. Four treatment levels of soil preparations applied to *P. hybrida* seedlings. The composition of the Thrive® fertilizer as shown in Table 2.

Treatments	**Soil composition**
Control mix (C)	Riversand + peat [3:1]
Workings (W)	Riversand + peat + **workings** [3:1:4]
Nitrogen (N)	Riversand + peat + **workings** [3:1:4] + **urea**
Fertiliser (F)	Riversand + peat [3:1] + **Thrive®** soluble all purpose fertiliser

The amount of urea used in the 'nitrogen' treatment was in direct proportion to the total nitrogen found in Thrive® soluble all purpose fertilizer (Table 2). Urea (44% nitrogen) was used because it is readily available and the nitrogen in Thrive® is mostly urea. 4 grams of Thrive® (containing 1.08 grams nitrogen) was added to 2 litres of water. This was half of the amount prepared in the first pot trial, since the number of replicates was half (5). This was done to maintain application rates to that of the previous pot trial. 2.455 grams urea (1.08 grams nitrogen) was also dissolved in 2 litres of water. As in Pot Trial #1, the treatment solutions were applied at the beginning of each week for the 4-week trial duration. Temperatures ranged from 3-35°C over the trial period (16 Aug.-13 Sept., 2006). Change in leaf number and height, number of flowers, and dry plant weight were documented. Statistical analysis methods were the same as in Pot Trial #1.

2.3 Field Trial (Alice Springs, NT)

The model used in the construction of the termite feeding stations followed the designs (with a few modifications) provided by Dr. John French. His model holds the theory that, because subterranean termites do not build above-ground mounds (although some colonies may experience some 'mounding' activity), an 'artificial mound' with a favourable food source may be employed to focus colonial feeding activity.

2.3.1 Preparation of 10 sites

The road west of the Bowerbird Tip Shop of Alice Springs, extending from Commonage Road, is approximately 500 metres in length. The roadside was surveyed for termite activity on living and dead trees, bushes, stumps, and logs (Figure 5). Samples were taken and species identified. Of the 10 sites marked out, four exhibited actual mounding activity around the base of the tree and up the trunk. This is typical of *C. acinaciformes* and samples were identified as such. The other active sites consisted of a tree stump, an electricity pole stump, two small dead trees, and two living bushes with dead wood surrounding. These were difficult to sample as, though termites were found, the woody material was relatively dry and soldiers were not found on some sites. Nonetheless, the samples taken from the other six sites were identified as a combination of *Shedorhinotermes* sp., *Microceratermes* sp., and *C. acinaciformes*.

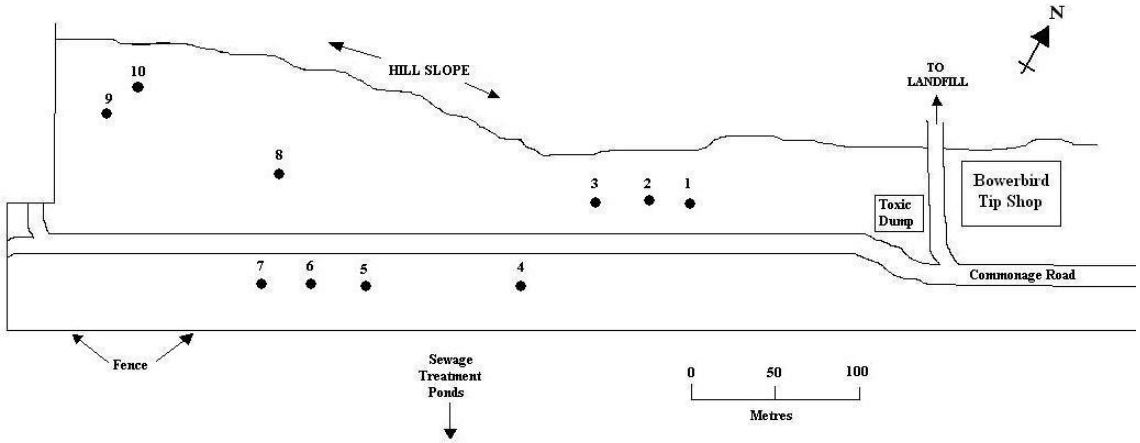

Figure 5. Map of the trial sites along the road extending west of Commonage Road, south of the landfill, Alice Springs.

2.3.2 Preparation of drums

Ten (44-gallon) plastic drums were thoroughly washed with water. They previously contained laundry detergents and were the only available containers of the same size and material. The tops were cut off and 30 holes (10mm diameter) drilled in the bottom of each for subterranean termite access. Four holes were drilled 16 cm up from the base on each drum using a 25 mm hole-saw. Poly-pipe (25 mm diameter) was cut at

approximately 10cm lengths, plugged at one end using the plastic cut-outs from the hole-saw and silicone sealant. These were inserted halfway into the 25 mm holes, functioning as temporary plugs and to house wet cardboard 'cigars' as an indicator of termite presence when removed and observed. Untreated pine was cut at lengths and arranged vertically to fill the drums just over halfway. This was salvaged from used planks of wood and pallets (Figure 6).

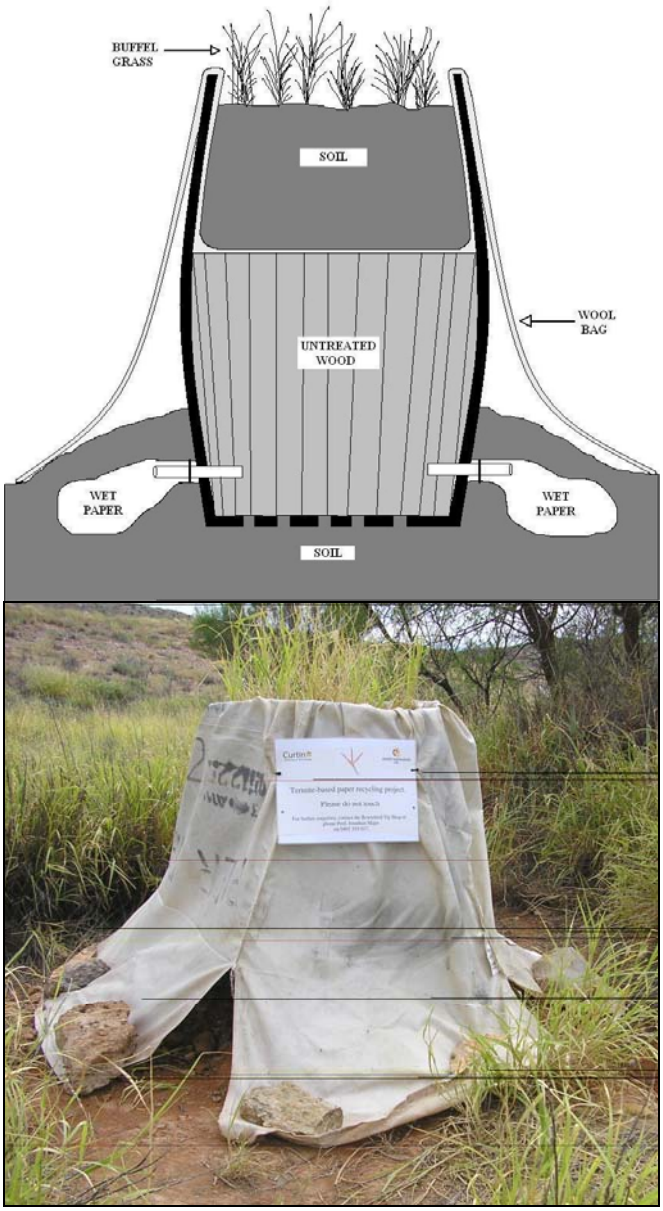

Figure 6. Transverse section of the termite feeding station (top), and photo of completed feeding station (bottom).

2.3.3 Setup of the feeding stations

The drums were transported to the 10 sites along with four drums of water. For each drum site, the debris and herb-layer vegetation was cleared using a shovel. A shallow pit was dug (about 20 cm) and thoroughly wetted. Two small pieces of untreated pine were placed in the pit, along with two handfuls of sawdust, and most of the dirt was replaced. This was wetted down again and the drum placed on top, leaving the drum set about 8 cm into the ground. Soil was shoveled around the sides to prevent entry by ants.

Also, for each drum, a large wool bag was placed inside touching the wood surface. The bag was filled with soil to about 10 cm from the rim of the drum and thoroughly wetted down. Buffel grass (*Cenchrus ciliaris*; a noxious weed covering most of the ground surface) was transplanted into the drum as a heat buffer, along with dead grass material (Figure 6). This arrangement was wetted again and the drums were marked with the site number. Where a tree, large stump, or bush existed, the drums were placed 1-1.5 metres away. One site consisted of a pile of decaying woody material (#6) and two of small dead trees/stumps (#8 and #9). For these three sites, the woody material on the surface was removed and drums placed directly on top of the active area.

2.3.4 Sampling for termite species and activity

The pine feeding stations were set up in mid-September 2005 and left until considerable termite activity was evident. Presence of termite activity was displayed by pulling the poly-pipe inserts out at the base of the drums and observing any termite individuals, as well as consumed cardboard and soil workings (Figure 7).

Amongst the active indicators, sampling of soldiers for species identification was somewhat difficult due to absence of them amongst the paper. In these cases, the cardboard indicators were placed back in the drums to allow communication to the soldiers of the disturbance. The plugs were left for 2-3 minutes and removed again; soldiers were placed in vials of 70% methylated spirits (the only available preservative). This disturbance-communication technique was employed to obtain soldiers for all active indicators.

According to the cardboard indicators, three drums were active within 4 weeks. Eight of the ten drums were active after 11 weeks.

Figure 7. Poly-pipe plug with cardboard 'cigar' showing termite activity (*C. acinaciformes*).

2.3.5 Preparation of the paper food source

For each of the 10 drums, four samples were prepared to utilise the four holes in the side-base of each one. The paper used was from a pile of discarded Yellow Pages® directories. For each sample, two books of paper were weighed and placed in thick transparent plastic bags. Three litres of water was added to each and allowed to soak into the paper prior to transportation to the drums. This was done to ensure an abundant supply of moisture without creating pools of water.

2.3.6 Setup of the paper food source

At each plug/hole site, a shallow pit was dug (20-25 cm) to house the sample. The plastic plug with silicone was removed using a pocket-knife and the poly-pipe was cleared of any cardboard and soil workings. The poly-pipe was replaced and the opening of the

sample bag wrapped around the poly-pipe. This was secured with a large cable-tie. Soil was mounded over the sample high enough to give a good cover over the sample as well as the poly-pipe termite access route (Figure 8). The hanging flaps of the wool-bag were placed over each mound and rocks used to secure them down (Figure 6). This was utilised to prevent erosion and increase buffering of heat. Each drum was then watered with 15-20 litres of water before leaving.

Figure 8. Setup of the paper food source showing the connected bag (left) and the soil mound (right).

2.3.7 Harvest of the paper samples

The paper samples were left in the field for 20 weeks to provide comparable data to that of the paper preference trials in the termitarium. As this study was focusing on the decomposing activity of the termites, only those bags exhibiting termite entry and activity were sent back to Perth. These bags were removed, sealed, and sent to Perth via courier for analysis (with Quarantine approval). As in the termitarium trials, the intact paper was removed from the workings and weighed separately. This was done as efficiently as possible, as some material, especially faecal pellets, was unable to be separated (Figure 9).

The remaining paper and separated workings were dried in a 60°C oven for 1 week to obtain dry weights. Data were used to obtain total (dry weight) decomposition, (dry

weight) workings, and moisture content. Results were analysed using one-way ANOVA and Scheffé the test.

Figure 9. Harvested paper samples showing soil and castings (left) and faecal pellets (right).

3.0 Results

3.1 Laboratory trials

3.1.1 Termitarium Trial #1

C. acinaciformes displayed a preference for newspaper over glossy-coated paper, and glossy over bleached office paper in the termitarium bed. The termites decomposed a total of 5.9 kg (dry weight) of paper, consisting of 3.3 kg newspaper, 2.0 kg glossy paper, and 0.6 kg office paper.

A one-way analysis of variance (ANOVA) revealed a statistically significant difference between the means of change in dry weight of the three paper types (newspaper, office paper, and glossy paper) after exposure to a captive colony of *C. acinaciformes* for 20 weeks at an alpha level of 0.01 ($F_{0.05\ (2)}$ [2,27] = 3.35, F cal. = 54.69 (P = 0.000)). The means for the change in dry weight of the newspaper, glossy, and office paper were -334.3 g, -198.8 g, and -60.1 g respectively (Figure 10).

A Scheffé test showed a statistically significant difference between the means of change in dry weight of all three paper types at the alpha level of 0.01. On average, the colony decomposed 135.5 g more newspaper than glossy paper, 138.7g more glossy paper than office paper, and 274.2 g more newspaper than office paper. Decomposition rates over the 20 weeks for the newspaper, glossy paper, and office paper averaged 16.7 g, 9.9 g, and 3.0 g per week respectively. Office sample #9 and glossy sample #3 exhibited no decomposition or signs of termite entrance into the containers. Newspaper sample #5 experienced the most decomposition of all samples (404.9 g, 50.2 %) (Figure 11).

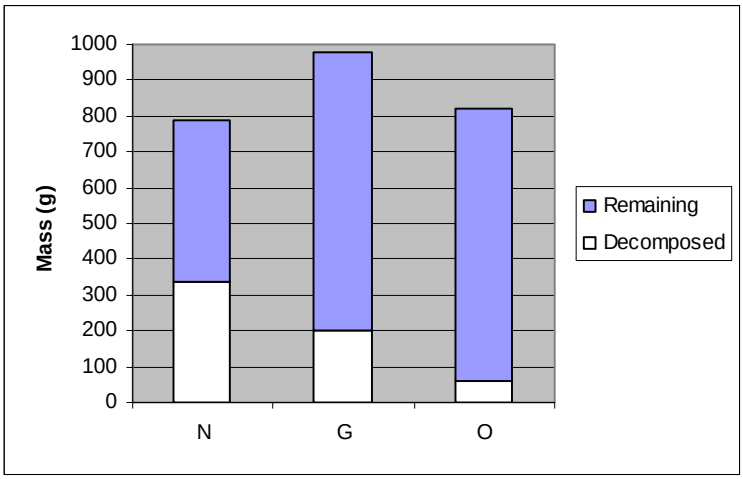

Figure 10. Average remaining and decomposed dry mass of newspaper (N), glossy paper (G), and office paper (O) samples after 20 weeks exposure to a captive colony of *C. acinaciformes*.

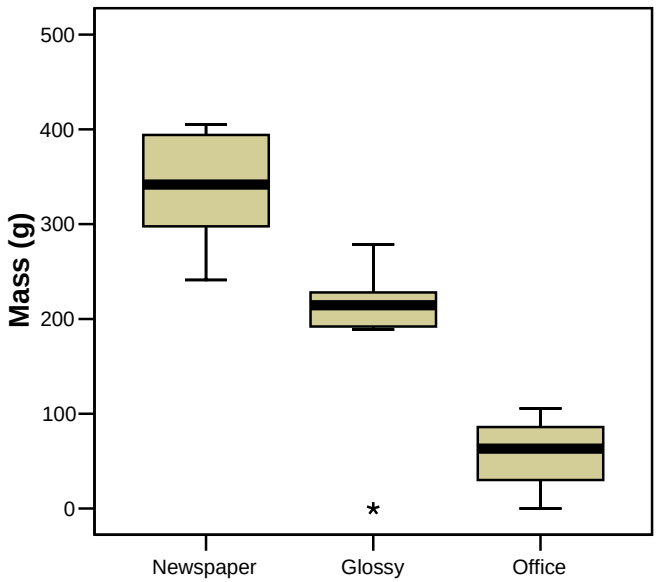

Figure 11. Boxplot of dry masses of decomposed paper for newspaper, glossy paper, and office paper (10 replicates).

As the dry mass for each paper type decreased over the 20 weeks, the average mass of the samples increased as a result of increased water composition and presence of the workings. The newspaper, glossy paper, and office paper experienced an increase in mass of water by 323.2 g, 369.0 g, and 277.1 g respectively within the paper and workings. The dry workings accounted for a further increase in mass of the newspaper, glossy paper, and office paper treatments by 352.1 g, 204.2 g, and 220.7 g, respectively (Figure 12).

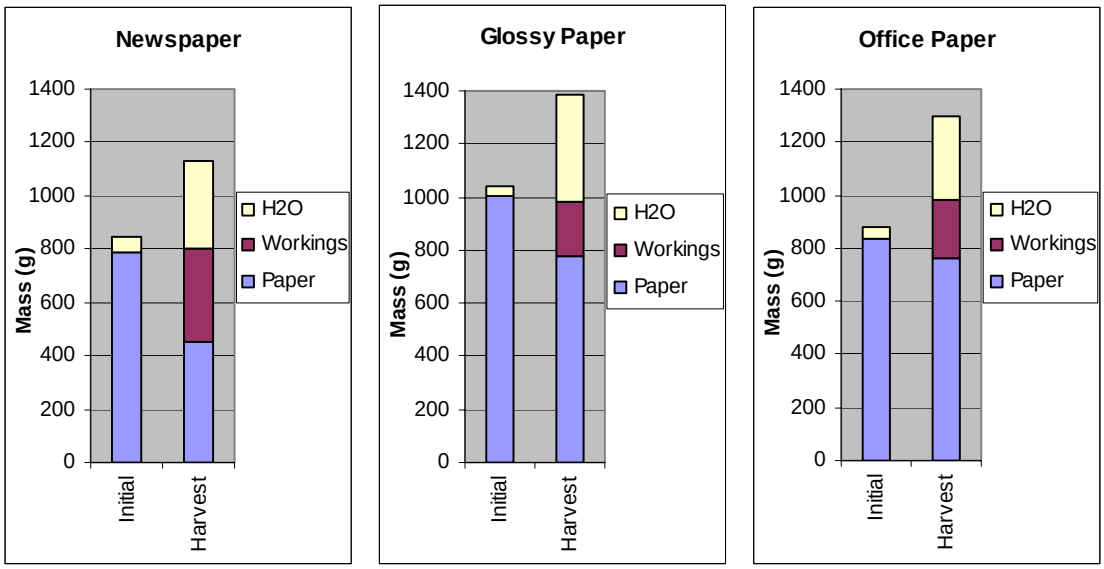

Figure 12. Average mass of water, dry workings, and dry paper within the newspaper, glossy paper, and office paper samples before (initial) and after (harvest) twenty weeks exposure to a captive colony of *C. acinaciformis*.

3.1.2 Termitarium Trial #2

C. acinaciformes displayed a preference for the dry glossy/newspaper mix (GND) over the glossy/newspaper mix saturated with water (GNW), and the GNW mix over the glossy paper in the termitarium bed. The termites decomposed a total of 6.9 kg dry weight of paper, consisting of 2.7 kg GND, 2.3 kg GNW, and 1.9 kg glossy paper.

Statistical analysis revealed no homogeneity of variance (P = 0.000) and no significant difference between means at an alpha level of 0.05 ($F_{0.05\,(2)}$ [2,12] = 3.88, F cal. = 3.145 (P = 0.080)). The glossy paper samples varied most in decomposition, with values varying from 176.6 g to 547.9 g (Figure 13). The means for change in dry weight of the GND,

GNW, and glossy paper treatments were -548.2 g, -462.6 g, and -375.4 g respectively (Figure 14).

On average, the colony decomposed 1.19 times more GND than GNW, 1.23 times more GNW than glossy paper, and 1.46 times more GND than glossy paper. Decomposition rates over the 20 weeks for GND, GNW, and glossy paper were 27.4 g, 23.1 g, and 18.8 g per week respectively. GND samples #1 and #5 were completely decomposed. Glossy paper sample #4 had the least amount of decomposition (176.6 g, 31.3 %), followed by glossy paper sample #5 (199.6 g, 34.0 %).

Most of the mass of the harvested samples was composed of workings and water. On average, the GND, GNW, and glossy paper samples contained 404.3 g, 253.9 g, and 444.4 g dry workings respectively. On average, the GND mix consisted of 161.5 g water (127.5 g increase). The GNW mix contained 215.3 g water (683.0 g decrease), and the glossy paper samples held 313.6 g water (294.5 g increase) (Figure 15).

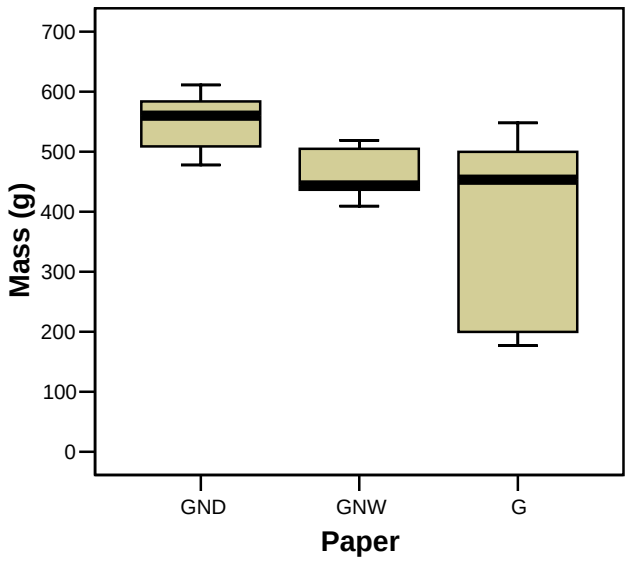

Figure 13. Boxplot of dry masses of decomposed paper for the glossy/newspaper mix (GND), glossy/newspaper mix saturated with water (GNW), and glossy paper (G) (5 replicates).

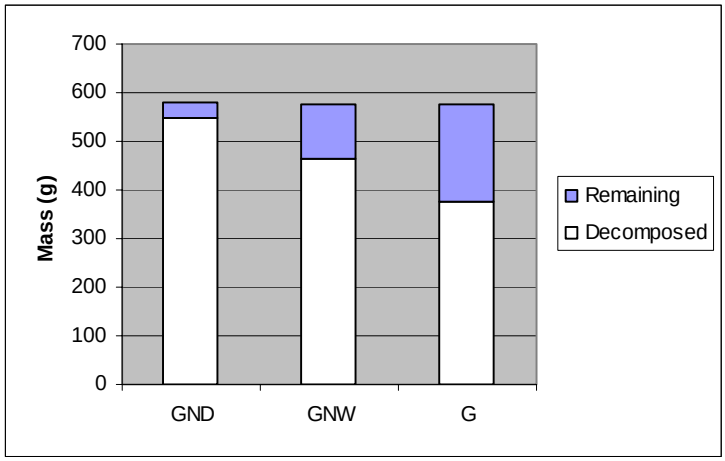

Figure 14. Average remaining and decomposed dry mass of a glossy/newspaper mix (GND), a glossy/newspaper mix saturated with water (GNW), and glossy paper (G) samples after 20 weeks exposure to a captive colony of *C. acinaciformes*.

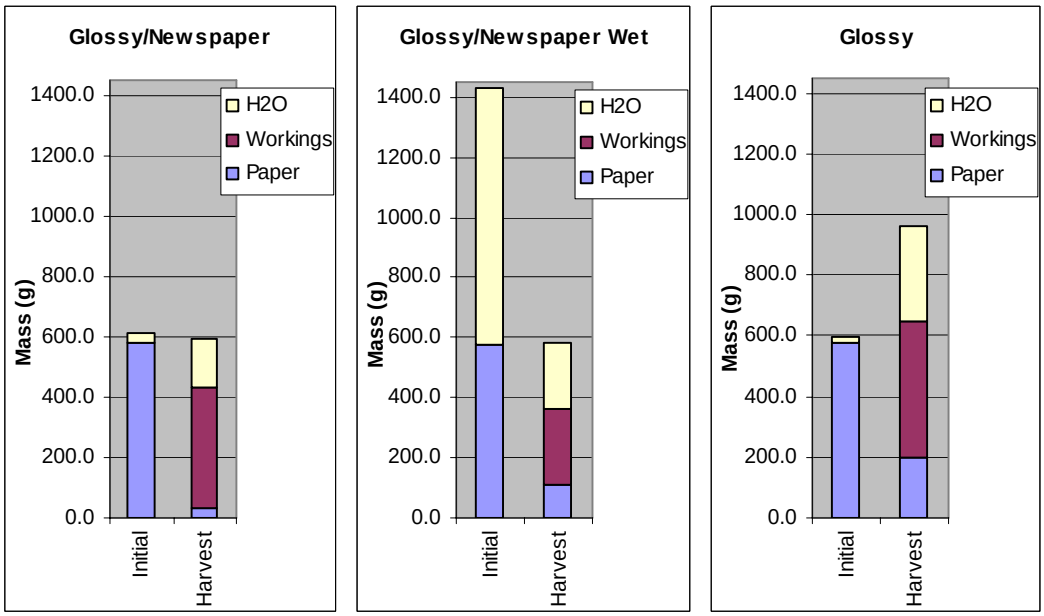

Figure 15. Average mass of water, dry workings, and dry paper within the glossy/newspaper, glossy/newspaper saturated with water, and glossy samples before (initial) and after (harvest) 20 weeks exposure to a captive colony of *C. acinaciformis*.

3.2 Analysis of termite workings

3.2.1 Pot Trial #1 using *P. hybrida*

The change in number of leaves and plant height, number of flowers and dry plant weight of *P. hybrida* seedlings during the 4 week pot trial are shown in Tables 4-7, respectively.

The addition of 50 % termite workings to an already infertile peat and river-sand control mix was shown to be less productive than the control, as shown by all measured plant variables (Tables 4-7).

The control, paper, workings, and fertiliser treatments experienced an average change in number of leaves by 11.4, 5.9, 10.7, and 44.7, respectively over the 4 weeks (Figure 16). A one-way analysis of variance for the change in number of leaves resulted in a statistically significant difference between means at an alpha level of 0.01 ($F_{0.05\ (2)}$ [3, 36] = 2.86, F cal. = 27.44) (P = 0.000). A Scheffé test exhibited a significant difference between the means of the fertiliser treatment and the control, paper, and workings at an alpha level of 0.05. No significant difference was seen between the other treatments (Table 4).

Table 4. Means of change in leaf number for the control, paper, workings, and fertiliser treatments in rank order, with 'like letters' indicating 'like means' (no significant difference) at an alpha level of 0.05 (P < 0.05).

Paper	Workings	Control	Fertiliser
5.9 [a]	10.7 [a]	11.4 [a]	44.7 [b]

The control, paper, workings, and fertiliser treatments displayed an average change in height of 6.9, 3.4, 4.4, and 11.8 cm, respectively (Figure 16). A one-way analysis of variance showed a statistically significant difference between means at an alpha level of 0.05 ($F_{0.05\ (2)}$ [3, 36] = 2.86, F cal. = 92.86) (P = 0.000). The Scheffé test displayed a significant difference between the means of change in height of all four treatments except the workings and paper treatments at an alpha level of 0.05 (Table 5). The fertiliser treatments averaged 1.7 times greater increase in height than the control, and 2.7 times greater than the workings treatments. The control averaged approximately 1.5 times greater increase in height than the workings, and 2 times greater than the paper treatments.

Table 5. Means of change in height (cm) for the control, paper, workings, and fertiliser treatments in rank order, with 'like letters' indicating 'like means' (no significant difference) at an alpha level of 0.05 (P < 0.05).

Paper	Workings	Control	Fertiliser
3.44 [a]	4.42 [a]	6.93 [b]	11.85 [c]

The means of number of flowers produced for the control, paper, workings, and fertiliser treatments were 6.1, 3.1, 4.7, and 8.1, respectively. A one-way analysis of variance showed a statistically significant difference between these means at an alpha level of 0.05 ($F_{0.05\ (2)}$ [3, 36] = 2.86, F cal. = 20.59) (P = 0.000). The Scheffé test indicated a significant difference between all means except the paper and workings, and the control and workings treatments at an alpha level of 0.05 (Table 6) (Figure 17).

Table 6. Means of number of flowers produced for the paper, workings, control, and fertiliser treatments in rank order, with 'like letters' indicating 'like means' (no significant difference) at an alpha level of 0.05 (P < 0.05).

Paper	Workings	Control	Fertiliser
3.1 [a]	4.7 [a b]	6.1 [b]	8.1 [c]

The control, paper, workings, and fertiliser treatments displayed an average dry plant weight of 0.958 g, 0.608 g, 0.721 g, and 1.544 g, respectively. A one-way analysis of variance showed a significant difference between these means at an alpha level of 0.05 ($F_{0.05\ (2)}$ [3, 36] = 2.86, F cal. = 58.10) (P = 0.000). The Scheffé test indicated a significant difference between all means except the paper and workings treatments at an alpha level of 0.05 (Table 7) (Figure 17).

Table 7. Means of dry plant weight (g) for the paper, workings, control, and fertiliser treatments in rank order, with 'like letters' indicating 'like means' (no significant difference) at an alpha level of 0.05 (P < 0.05).

Paper	Workings	Control	Fertiliser
0.608 [a]	0.721 [a]	0.958 [b]	1.544 [c]

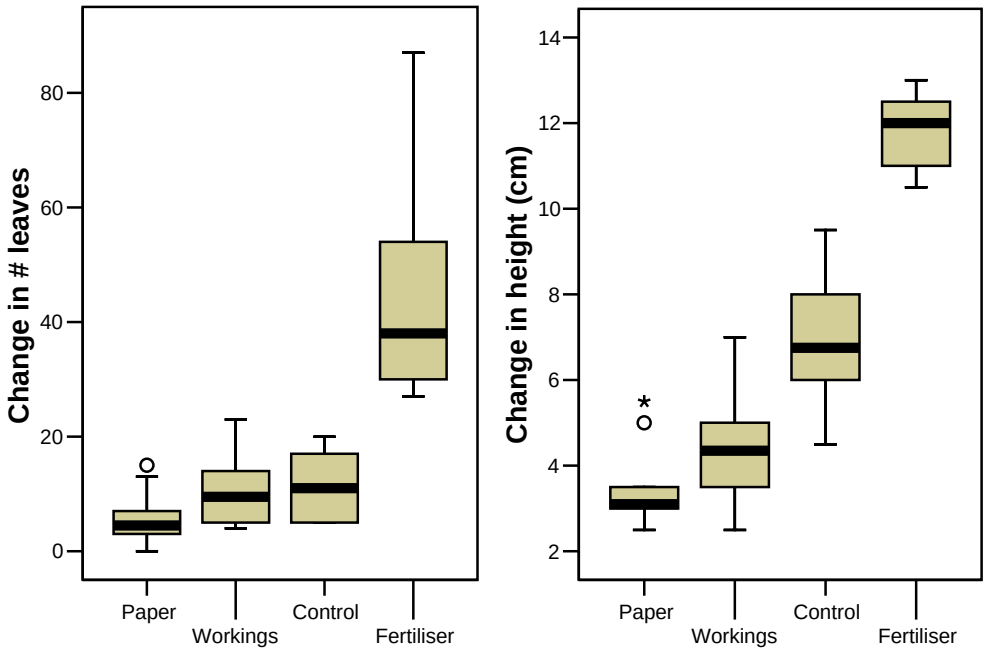

Figure 16. Boxplots of change in number of leaves (left) and change in height (cm) (right) produced by *P. hybrida* within the paper, workings, control and fertiliser treatments 4 weeks after propagation (10 replicates).

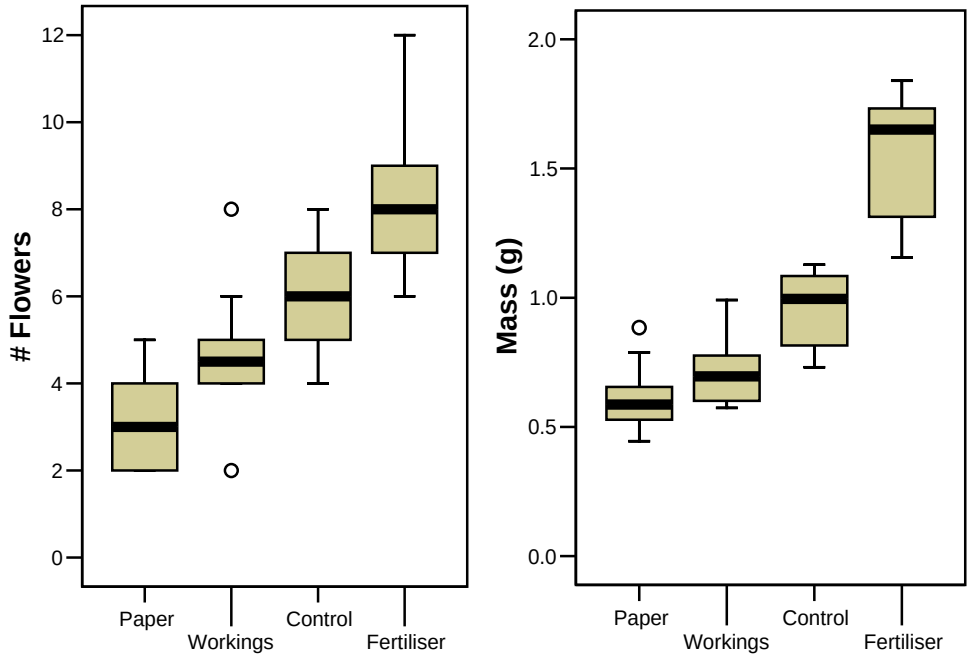

Figure 17. Boxplots of number of flowers (left) and dry plant mass (right) produced by *P. hybrida* within the paper, workings, control and fertiliser treatments 4 weeks after propagation (10 replicates).

3.2.2 Nutrient Analysis

Soil analysis of available nutrients in the termite workings revealed high levels of phosphorus, potassium, sulphur, organic carbon, iron, trace zinc, and trace iron, and increased conductivity and pH when compared to the control. Analysis of total nutrients within the dried plant material of Pot Trial #1 showed lower levels of nitrogen uptake from the workings, but higher levels of phosphorus, potassium, calcium, and iron than the control. An analysis of total nutrients in the three paper types and their workings displayed the highest levels of most nutrients in glossy paper, followed by newspaper, and a consistency in these ratios within the workings.

3.2.2.1 Soil Analysis of Available Nutrients

The paper treatment consisted of 50 % control mix (by volume). It is possible that most of the ground paper was sifted out during preparation for analysis, as it may not have been fine enough to pass through the sieves. Nonetheless, according to the CSBP soil analysis of the treatments for pot trial #1 before propagation of *P. hybrida*, the ground paper contributed no nutrients of horticultural significance when compared to the control (Table 8).

Calculated on the basis that the workings mix contained 50% control mix, the workings contributed to the control mix 74 mg/kg phosphorus, 47 mg/kg potassium, 67 mg/kg sulphur, 2.6 % organic carbon, 828 mg/kg iron, 0.09 mg/kg copper, 2.21 mg/kg zinc, 0.47 mg/kg manganese, and 50 mg/kg trace iron. The workings mix differed from the control in having 38 times more phosphorus, 3.9 times more potassium, 23.7 times more sulphur, 3.3 times more organic carbon, 19.5 times more iron, 1.4 times more copper, 8.3 times more zinc, and 2.1 times more manganese. The workings treatments accounted for approximately one half of the ammonium found in the control mix and very low levels of nitrate. The workings also increased the conductivity (from 0.08 dS/m to 0.25 dS/m) and pH (from 4.96 to 8.18) (Table 8).

The fertiliser treatments showed higher levels of nitrate, ammonium, phosphorus, potassium, and sulphur than the control. The workings showed 2.6 times more

phosphorus, 4.9 times more sulphur, 4 times more organic carbon, 24.8 times more iron, 10.9 times more zinc, and 6.6 times more available iron (trace) than the fertiliser treatments (Table 8).

Compared to the soil in the termitarium trial bed, the workings revealed lower levels of nitrogen, phosphorus, potassium, sulphur, iron, zinc, manganese, and trace iron as well as lower conductivity. The workings contained higher levels of organic carbon, similar amounts of copper, and a higher soil pH (Table 8).

TABLE 8. Comparison of available nutrient concentrations within the paper, control, fertiliser, and workings soil treatments before propagation of *P. hybrida*, and in the termitarium trial bed (means of 5 sub-sample replicates).

		Paper	Control	Fertiliser	Workings	Trial Bed
Nitrate	mg/kg	1.00	1.00	20.60	1.00	13.40
Ammonium	mg/kg	9.80	11.60	77.80	4.60	8.20
Phosphorus	mg/kg	2.00	2.00	29.00	76.00	138.83
Potassium	mg/kg	17.60	16.00	67.60	63.00	130.60
Sulphur	mg/kg	3.32	2.96	14.18	70.12	305.20
Organic carbon	%	1.25	1.15	0.94	3.75	2.70
Iron	mg/kg	29.80	44.80	35.20	873.00	2001.00
Conductivity	dS/m	0.03	0.08	0.15	0.25	0.62
pH CaCL2		3.56	3.56	4.18	7.26	5.94
pH H2O		4.98	4.96	5.70	8.18	6.28
Cu (trace)	mg/kg	0.24	0.25	0.31	0.34	0.35
Zn (trace)	mg/kg	0.28	0.30	0.23	2.51	3.84
Mn (trace)	mg/kg	0.40	0.44	1.01	0.91	1.20
Fe (trace)	mg/kg	8.70	10.51	9.12	60.59	205.25

3.2.2.2 Plant analysis of total nutrients

According to the dry plant material taken from the pot trial one month after propagation, nitrogen was the main limiting factor in the growth of the plants when compared to the control and fertiliser treatments. This is especially seen in the soil analysis (Table 8).

The addition of ground paper was shown to produce a less productive soil medium for plant productivity. The paper treatments showed nutrient amounts less than all other treatments.

The main nutrients (nitrogen, phosphorus, and potassium) allowed more growth in the fertiliser treatments than the control, and more in the control than the workings. The plant material in the fertiliser treatments contained 4.4 times more nitrogen, 3.5 times more phosphorus, and 2.0 times more potassium than the control.

The plant material of the workings treatments showed 56 % of the nitrogen, 86 % of the phosphorus, and 84 % of the potassium found in the control. The material also contained generally less of the rest of the nutrients, but slightly higher amounts of trace iron than the control and workings treatments (Table 9).

TABLE 9. Amount of nutrients (mg) within the dry plant material of the paper, workings, control, and fertiliser treatments one month after propagation of *P. hybrida* (10 dried plants divided into 5 sub-sample replicates for each treatment).

(mg)	**Paper**	**Workings**	**Control**	**Fertiliser**
Nitrogen	716.22	821.94	1454.24	6423.04
Phosphorus	137.16	190.92	221.11	790.53
Potassium	1145.11	1553.03	1856.22	3705.91
Sulphur	195.53	298.21	338.94	503.96
Sodium	623.69	710.76	1399.06	2086.56
Calcium	420.61	673.13	744.37	841.79
Magnesium	128.17	176.36	268.81	380.13
Chloride	0.00	1657.58	4459.30	7368.59
Copper	0.03	0.03	0.05	0.06
Zinc	0.03	0.03	0.04	0.06
Manganese	0.03	0.03	0.05	0.06
Iron	0.40	0.54	0.37	0.39
Nitrate	0.00	0.06	0.08	1.74
Boron	0.01	0.01	0.02	0.04
Molybdenum	0.00	0.00	0.00	0.00

3.2.2.3 Paper and workings analysis of total nutrients

The analysis of total nutrient content in the glossy paper, newspaper, and office paper with their workings showed the presence of all nutrients found to be available in the soil test and taken up by the plants in excess to the nutrients found in the control mix.

Throughout the decomposition process, nitrogen and potassium in the paper decreased in concentration (accounting for the mass of soil brought up in the workings), while phosphorus accumulated.

Glossy paper showed the highest level of most nutrients, being second to newspaper, and the ratios were consistent with the workings left in the termitarium containers (Table 10). These nutrients are nitrogen, potassium, sulphur, sodium, calcium, magnesium, copper, zinc, manganese, iron, and boron. The three paper types held similar amounts of phosphorus. High levels of calcium were seen in the glossy paper, being second to the office paper, and the ratios were consistent with their relative workings. High levels of iron in the workings when compared to the paper may be attributed to the soil brought up by the termites from the termitarium bed (Table 10).

TABLE 10. Average results of five replicates for total nutrient analysis of glossy, newspaper, and office paper and workings (mg/kg) (converted from percentages).

Total Nutrients (mg/kg)	Glossy Paper	Newspaper	Office Paper	Glossy Workings	Newspaper Workings	Office Workings
Nitrogen	3346	3298	3170	1588	1608	1434
Phosphorus	200	200	200	360	304	336
Potassium	552	362	318	200	200	200
Sulphur	648	388	386	658	540	550
Sodium	1552	790	1350	472	234	456
Calcium	57370	1924	39112	7356	2986	4584
Magnesium	1032	322	596	140	200	200
Chloride	0	0	0	0	0	0
Copper	65.2	21.6	3.9	12.1	9.4	9.5
Zinc	4.3	3.4	2.8	11.9	11.0	13.2
Manganese	16.3	6.2	5.1	6.9	6.1	6.0
Iron	371.2	174.8	95.6	2791.3	2442.2	2869.0
Nitrate	0.0	0.0	0.0	0.0	0.0	0.0
Boron	2.0	1.9	3.1	2.5	1.7	2.0
Molybdenum	0.0	0.0	0.0	0.0	0.0	0.0

3.2.3 Pot Trial #2 (*P. hybrida*)

The addition of nitrogen (in the form of urea) to the workings mix increased the plant productivity of *P. hybrida* seedlings substantially when compared to the control and fertiliser treatments. The nitrogen in Thrive® all purpose fertiliser has a small component of nitrate and ammonium, but most of it is made up of urea. The workings plus nitrogen and fertiliser treatments nonetheless received the same applications of nitrogen in aqueous solution over the 4 weeks (1.08 g/2 L water).

The means for change in number of leaves one month after propagation for the workings, control, workings plus nitrogen, and fertiliser treatments were 13.8, 19, 167.6, and 205.2, respectively (Figure 18). A one-way analysis of variance displayed a significant difference between these means at an alpha level of 0.01 ($F_{0.05\,(2)}$ [3, 19] = 3.13, F cal. =258.9) (P = 0.000). The Scheffé test indicated a significant difference between all means except the control and workings treatments at an alpha level of 0.05 (Table 11). The workings plus nitrogen treatments produced on average 8.8 times more leaves than the control and 12.1 times more leaves than the workings without nitrogen. The fertiliser treatments produced 1.2 times more leaves than the workings plus nitrogen.

Table 11. Means of change in number of leaves for the workings, control, workings + N, and fertiliser treatments in rank order, with 'like letters' indicating 'like means' (no significant difference) at an alpha level of 0.05 (P < 0.05).

Workings	Control	Workings + N	Fertiliser
13.8 [a]	19.0 [a]	167.6 [b]	205.2 [c]

The means for change in height (cm) for the workings, control, workings plus nitrogen, and fertiliser treatments were 4.4 cm, 4.3 cm, 6.3 cm, and 5.9 cm respectively. The figures showed a lack of homogeneity of variance (Figure 18).

The means for the number of flowers for the workings, control, workings plus nitrogen, and fertiliser treatments were 1.2, 2.2, 2.6, and 3.4, respectively (Figure 19). A one-way analysis of variance displayed a significant difference between these means at an alpha level of 0.05 ($F_{0.05\,(2)}$ [3, 19] = 3.13, F cal. =3.719) (P = 0.033). The Scheffé test indicated a significant difference between the workings and fertiliser treatments at an alpha level of 0.05 (Table 12).

Table 12. Means of number of flowers for the workings, control, workings + N, and fertiliser treatments in rank order, with 'like letters' indicating 'like means' (no significant difference) at an alpha level of 0.05 (P < 0.05).

Workings	Control	Workings + N	Fertiliser
1.2 [a]	2.2 [a b]	2.6 [a b]	3.4 [b]

The means for change in dry mass for the workings, control, workings plus nitrogen, and fertiliser treatments were 0.688 g, 0.866 g, 1.680 g, and 2.992 g, respectively (Figure 19). A one-way analysis of variance displayed a significant difference between these

means at an alpha level of 0.05 ($F_{0.05\ (2)}$ [3, 19] = 3.13, F cal. =108.8) (P = 0.000). The Scheffé test indicated a significant difference between all means except the control and workings treatments at an alpha level of 0.05 (Table 13). The workings plus nitrogen treatments produced on average 1.94 times more dry mass than the control and 2.51 times more dry mass than the workings. The fertiliser treatments produced 1.78 times more dry mass than the workings plus nitrogen.

Table 13. Means of change in dry mass (g) for the workings, control, workings + N, and fertiliser treatments in rank order, with 'like letters' indicating 'like means' (no significant difference) at an alpha level of 0.05 (P < 0.05).

Workings	Control	Workings + N	Fertiliser
0.668 [a]	0.866 [a]	1.680 [b]	2.992 [c]

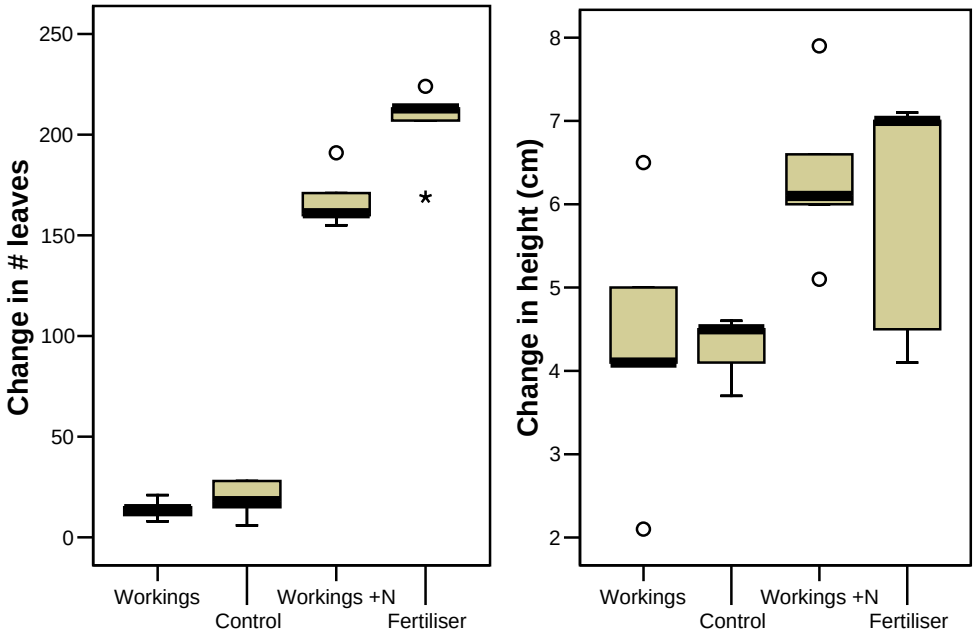

Figure 18. Boxplots of change in number of leaves (left) and change in height (right) produced by *P. hybrida* within the workings, control, workings + N and fertiliser treatments 4 weeks after propagation (5 replicates).

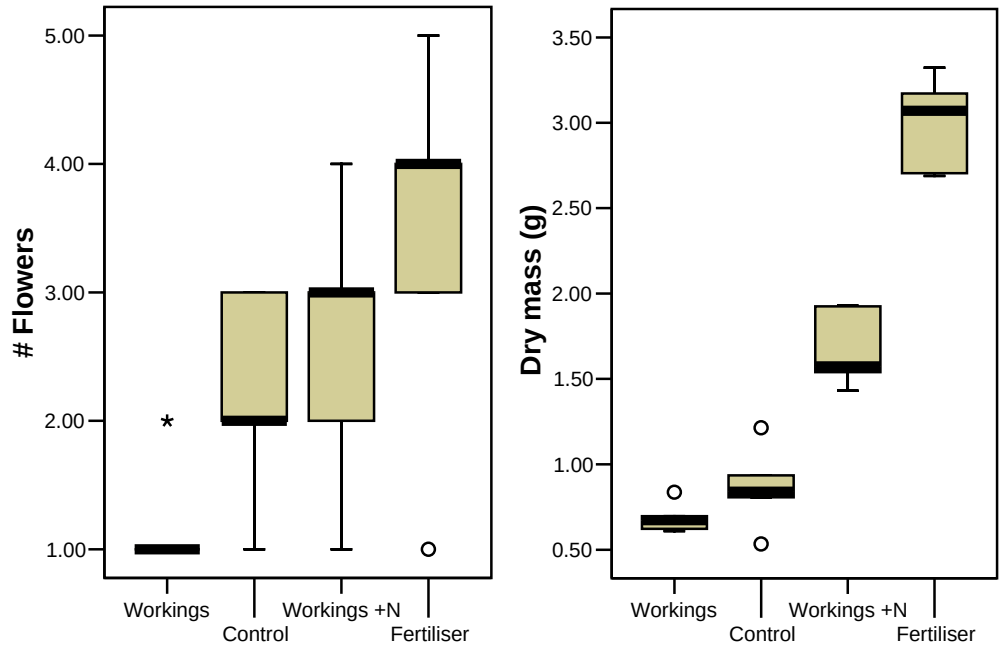

Figure 19. Boxplots of number of flowers (left) and dry plant mass (right) produced by *P. hybrida* within the workings, control, workings + N and fertiliser treatments 4 weeks after propagation (5 replicates).

3.3 Field Trial (Alice Springs)

All drums experienced as least some termite activity in regards to the paper. Drums #1, #2, #3, #5, and #6 contained *C. acinaciformes* within the bags, and this was consistent with samples taken from the drums previous to the paper trial. Drums #7 and #8 showed termite workings at the site, but no activity in the drums when the bags were connected. Drum #8 contained *C. acinaciformes* with two active bags, while drum 7 had one active bag with no soldiers to identify. Drums #4, #9, and #10 were identified to contain *Shedorhinotermes* sp. This was consistent with the individuals found in connected bags, in exception to drum #4 which had no soldiers to identify (Table 14). The low termite numbers in the bags may be due in part to the fact that the bags were removed during the mid-day heat.

Although the local subterranean termite population was shown to have entered and become active in the feeding stations, decomposition of the paper samples was relatively low.

TABLE 14. Number of termites and species identified where soldiers were present in the bags and in the drums before the paper trial (NA = 'no activity', NS = 'no soldiers').

Drum #	Bearing	termites in bag	Species in bag	Species in drum	Initial species and site description
1	S	6	*C. acinaciformes*	*C. acinaciformes*	NS (mounding on live tree)
	E	19	*C. acinaciformes*		
	N	0			
	W	0			
2	W	NA		*C. acinaciformes*	*C. acinaciformes* (mounding on live tree)
	S	0			
	E	2	*C. acinaciformes*		
	N	10	*C. acinaciformes*		
3	W	0		*C. acinaciformes*	*C. acinaciformes* (mounding, cut off telephone pole)
	S	2	*C. acinaciformes*		
	E	1	NS		
	N	2	*C. acinaciformes*		
4	W	NA		*Schedorhinotermes sp.*	*Shedorhinotermes sp.* *Microcerotermes* sp. (dead shrub and wood)
	S	4	NS		
	E	NA			
	N	NA			
5	S	6	*C. acinaciformes*	*C. acinaciformes*	*Microceratermes* sp. (mounding on stump, very dry)
	E	0			
	N	4	NS		
	W	1	NS		
6	N	7	*C. acinaciformes*	*C. acinaciformes*	*C. acinaciformes* (logs and wood with workings)
	E	57	*C. acinaciformes*		
	S	0			
	W	NA			
7	N	NA		NA	NA (half-dead shrubs with workings)
	E	0			
	S	NA			
	W	NA			
8	E	NA		NA	NA (workings up live tree, no mounding)
	S	0			
	W	35	*C. acinaciformes*		
	N	NA			
9	N	0		*Shedorhinotermes sp.*	NS (dead shrub)
	E	5	NS		
	S	28	*Shedorhinotermes sp.*		
	W	43	NS		
10	E	NA		*Shedorhinotermes sp.*	NS (half-decomposed log next to live tree)
	S	247	*Shedorhinotermes sp.*		
	W	0			
	N	NA			

The bearing of the bags in relation to the drums had no effect on decomposition (refer to Appendix C). The west bag of drum #9 showed the most decomposition of paper over the 20 weeks of 561.6 g (20.8 %) dry mass, followed by the north bag of drum #5 with 224.2 g

(8.3 %). Four of the bags which showed decomposition increased in dry mass of material due to irremovable faecal pellets (Table 15). This shows the difficulty in quantifying accurate decomposition of samples. Ten of the 40 bags connected to the 10 drums showed no signs of termite entrance or activity.

TABLE 15. Four of the 30 active bags which showed decomposition, but increased in dry mass (g) of the samples due to irremovable faecal pellets.

Drum #	Bearing	Increase in dry mass (g)
1	E	123.3 (104.5%)
4	W	101.1 (103.7%)
4	N	124.5 (104.6%)
7	E	15.7 (100.6%)

Combining the bags, the drum with most decomposition was drum #9, exhibiting 783 g (7.0 %) decomposed dry mass, followed by drum #5 with 545 g (5.0 %). Drum #5 contained the most workings (4.33 kg dry) in all four active bags. Drum #7 showed the least decomposition (47 g dry), with one active bag (Table 16) (Figure 20).

TABLE 16. Results of total decomposition and dry workings (g) for the sum of active bags (30 in total) per drum 20 weeks after being connected, including the number of non-active bags and drum placement (NM = next to tree mounding, N = next to active area, T = on top of active area).

Drum #	Placement	# Non-active bags	Total decomposition (g)	% decomposition	Total workings (g)
1	NM	0	62	0.6%	2760
2	NM	1	287	3.5%	3455
3	N	0	328	3.0%	3134
4	N	1	-79	-0.9%	301
5	N	0	545	5.0%	4331
6	T	1	279	3.4%	1357
7	N	3	-16	-0.6%	47
8	T	2	252	4.7%	285
9	T	0	783	7.0%	286
10	N	2	350	6.5%	117

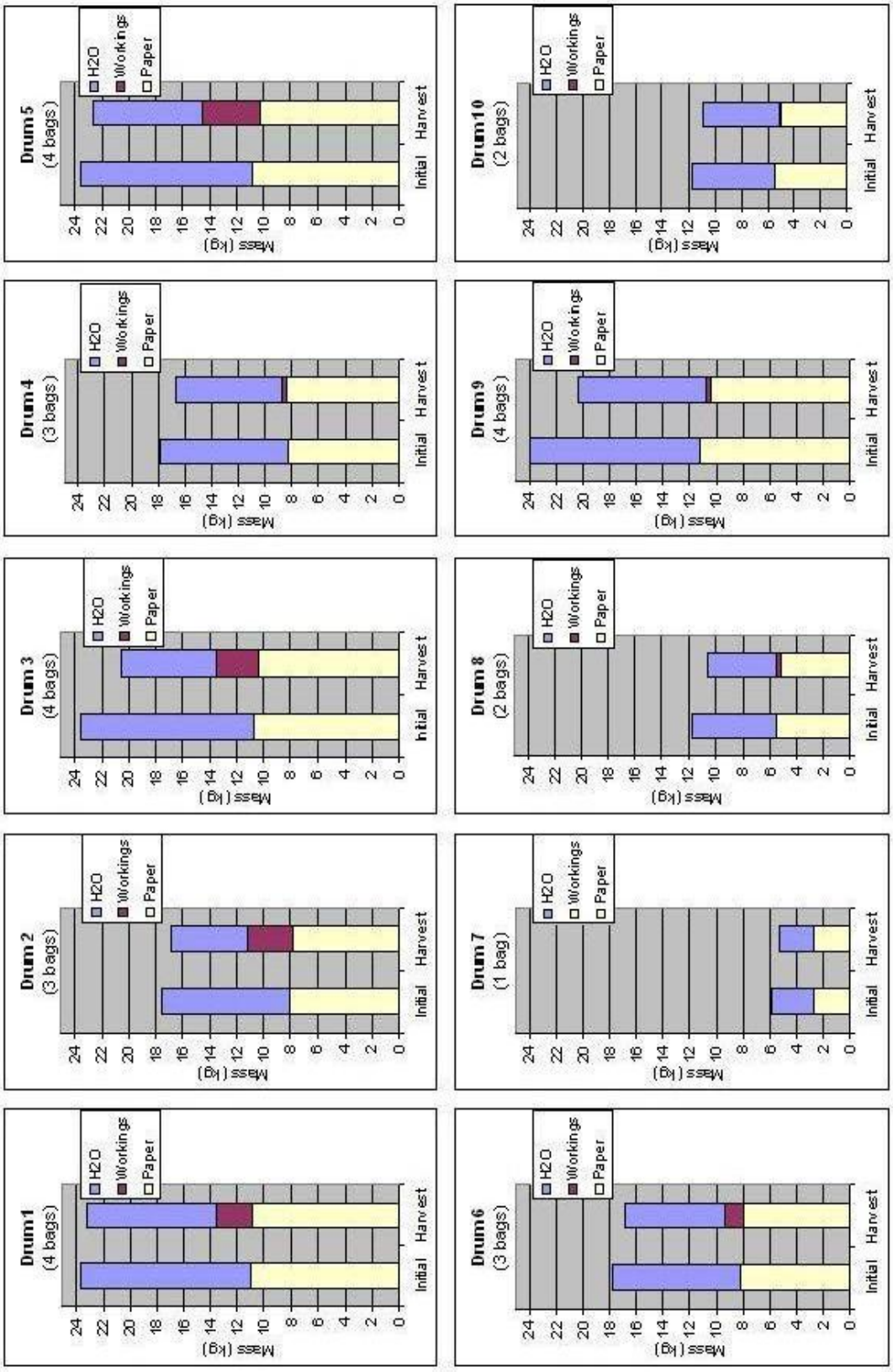

Figure 20. Total mass of H2O, dry workings, and dry paper (kg) per drum within the bags exhibiting termite activity before (initial) and after (harvest) twenty weeks exposure to the drums.

Accounting for the active bags, the loss of moisture varied among drums. Drum #3 had the highest loss of moisture (5.78 kg, 45.5 %) with 4 active bags. Drum #10 had the lowest (0.55 kg, 8.7 %), accounting for two active bags (Table 17).

TABLE 17. Results of moisture loss (g) and percent moisture loss within active bags for each drum.

Drum #	Moisture loss (g)	% moisture loss
1	3107.1	24.4%
2	3958.9	41.5%
3	5783.2	45.5%
4	1542.5	16.1%
5	4706.7	37.0%
6	2039.8	21.4%
7	758.7	23.8%
8	1217.2	19.1%
9	3231.5	25.3%
10	555.9	8.7%

4.0 Discussion

C. acinaciformes was efficient in decomposing waste paper when given favourable environmental conditions. Workings left behind revealed residues with nutrients of horticultural significance that may be suitable for mixing with native soils, especially as a source of organic carbon, trace elements, and possibly phosphorus and potassium, and also to increase the pH of acidic soils. Although the pine feeding stations were effective in focusing the feeding behaviour of the termites, the decomposition of paper in the bags in the field was relatively low.

4.1 Laboratory trials

The two trials performed in this pilot study revealed behavioural patterns of a colony of *C. acinaciformes*, given favourable conditions and waste paper food sources. These conditions were high humidity, controlled lighting and temperature, constant water supply, and suitable soil (i.e. unsaturated and spatially enough for moving and gallery building). These preconditions for rearing termites have been described by Krishna and Weesner (1969). The termitarium was also designed with the soil beds directly connected and in

close proximity to the housed queen, although this distance may not be exactly the same in nature.

Within the cubic metre soil bed, the termites were just as aggressive towards lignocellulosic waste as they were toward timber and wood products. This supports the documented literature on the capacity of *C. acinaciformes* to effectively prospect for and decompose cellulosic materials (Creffield, 1996; Hadlington, 1987; Martin, 1983). In both paper trials, over 50 % of the containers were invaded within the first 3 days. Even though the termites were given limited access to the food source via small holes in the bottom of the jars, soil and moisture were quickly brought up from the soil bed and mud tubes formed so that the paper samples became completely encased in termite castings. For many of the sample containers (especially in Trial #2), the thick plastic lids were chewed through and aerial mud tubes were constructed, perhaps in an attempt to aerate the containers (Figure 21). *Kalotermes flavicollis* and *Reticulitermes lucifugus santonensis* have displayed the same behaviour under similar laboratory conditions and using polyethylene containers (Krishna & Weesner, 1969). The ability of termites to chew through non-lignocellulosic material such as plastic is significant, since the number of animals attacking similar material under natural conditions may be extremely high compared to a laboratory colony (Krishna & Weesner, 1969).

Figure 21. Sample containers in the termitarium showing aerial mud-tubes that had formed after the termites had chewed through the plastic lids.

4.1.1 Termitarium Trial #1

The colony preferred newspaper over glossy-coated paper, and glossy over bleached office paper. These papers differ physically and chemically due to variable fibre sources and different manufacturing processes for end-use quality (Roberts, 1996). Approximately 40 % of all paper produced throughout the world is used for purposes of communication (newsprint, printing, writing, etc.), while over 50 % is used for packaging and tissue (Roberts, 1996). The paper used in the two trials represented the first-mentioned category, and varied in its mechanical processing (i.e. fibre length) and chemical composition (i.e. inks, dyes, lignin, and surface, strength, and bleaching additives).

Newspaper was the closest in composition to the original wood produced by plants in that it had a longer fibre length, required less manufacturing chemicals such as bleaching agents, and had similar amounts of cellulose, hemicellulose, and lignin (Roberts, 1996). It had also been made in an acidic system similar to the naturally low pH of ground-wood pulp (Roberts, 1996). Therefore, the physical and chemical similarities to natural wood were probably the cause of preference for newspaper.

Glossy and office paper types have gone through further mechanical and chemical processes to reduce fibre length and lignin concentration, respectively, in order to provide a higher grade of paper (Roberts, 1996). The preference of glossy paper (i.e. magazines and catalogs) over printed office paper may be more difficult to explain. One reason may be the fact that glossy paper had revealed a much higher concentration of potassium, sulphur, calcium, magnesium, and trace elements (Table 10). These results confirm the use of inorganic fillers, such as clay, alum, and precipitated calcium carbonate, which are used in the production of magazine paper to improve sheet characteristics (McKinney, 1995). The fillers and inks may comprise a percentage mass as high as 50 % and 7 %, respectively, as the magazine paper used in the trials had been coated on both sides (McKinney, 1995). Magazine paper is also produced from several grades of paper (McKinney, 1995). If this is the case, then glossy magazine-type paper has a more variable cellulose fibre length, contains more nutrients that the termites can utilise, and contains less overall cellulose to decompose per unit mass.

The fact that *C. acinaciformes* decomposed a quantity of all three paper types gives support to the literature on their ability to metabolise and eliminate toxic polychlorinated biphenyls (PCB's) from inks and dyes (Haritos *et al.*, 1993). The evolutionary significance of this detoxification system may stem from the ability of termites to decompose most wood types containing a variety of allelochemicals (Haritos *et al.*, 1993).

4.1.2 Termitarium Trial #2

Mixing newspaper with glossy paper substantially increased the overall decomposition of paper. The GNW mix consistently decomposed more than the glossy samples, but slightly less than the GND, and the glossy paper samples showed much more variability. It is unlikely that environmental or seasonal conditions would have contributed to this outcome in the two trials, as the conditions inside the termitarium remained the same. In both trials, the other two soil beds adjacent to the test bed contained blocks of softwood which the termites were feeding on. Behavioural and biological changes are known to take place seasonally within colonies of subterranean termites when they prepare for the nuptial flight. The colony, however, had not had a nuptial flight since captivity 6 years prior, perhaps due to the favourable conditions in the laboratory.

The addition of moisture in the GNW treatments increased the overall decomposition of all other treatments when compared with Trial #1. The GNW samples decreased in moisture substantially throughout the trial and, as the GND samples revealed higher decomposition, the moisture may have been transported from the GNW samples to the GND and glossy paper treatments.

Water relations in many termite genera have been documented (Krishna & Weesner, 1969). Although the family Rhinotermitidae is known to have a high and constant environmental moisture requirement, too much may cause 'water poisoning' or fungal attack (Krishna & Weesner, 1969). The optimal level of moisture for termites has been shown to be dependent on the water-holding capacity of the particular soil (Krishna & Weesner, 1969). The GNW samples were saturated with water, and this is perhaps why they were decomposed consistently, although not significantly less than the GND samples. Also, the termites constructed aerial mud-tubes through the lids of all of the GNW

containers, perhaps in an attempt to rid the samples of excess moisture via evaporation. Thus mixing newspaper with glossy paper, as well as adding moisture to sub-levels, is an effective method to employ in the biogenic conversion of waste paper by termites.

4.2 Analysis of termite workings

The remaining workings in the termitarium containers were analysed for nutrients of horticultural significance by two pot trials and by CSBP nutrient analyses. This was done in an attempt to answer the question of whether the decomposition of paper by termites led to nutrient-rich material as a conversion product which can be utilised in horticultural practices. The results have shown this to be so, but with levels of certain nutrients needing to be augmented. The termite remains in the containers also have the capacity to increase the pH of acidic soils and the amount of organic carbon, which would stimulate plant growth and the activity of soil flora and fauna (Atwell *et al*., 1999).

The first pot trial involved propagation of *P. hybrida* in a medium of termite workings from the Termitarium Trial #1, plus river sand and peat (4:3:1). The plant growth revealed this soil medium to be less productive than an already infertile sand and peat (3:1) control mix. Addition of ground paper to this control mix (1:1) was even less productive, perhaps because of microbial activity utilising the nutrients to break down the high cellulose content of the soil. The soil analysis of this workings treatment, however, revealed 38 times more phosphorus than the control, and 2.6 times more than the fertiliser treatment (Thrive® all purpose fertiliser applied according to the manufacturer's recommendations). The workings mix also contained high levels of potassium, sulphur, organic carbon, and the trace elements copper, zinc, manganese, and iron, while revealing a pH of 8.18.

The limiting nutrient in plant production within the workings was nitrogen. Nitrogen deficiencies affect all processes of growth and metabolism (Atwell *et al*., 1999). It was confirmed, by the analysis of dried plant material from the pot trial, that nitrogen deficiency affected uptake of the other nutrients. This led to the second trial involving added nitrogen in the form of urea.

Adding aqueous urea to the workings mix increased plant productivity substantially, suggesting that the concentrations of the other nutrients in the workings mix were genuinely beneficial to plant growth (Table 8). The next question, then, is "Where did the nutrients come from, the soil or the paper?"

The ground glossy paper, newspaper, and office paper with their workings were analysed for total nutrient content. It is difficult to quantitatively relate the total nutrients in the paper to the plant-available nutrients found in the soil analysis due to chemical changes during decomposition, movement of nutrients by the termites out of the containers, integration of nutrients into biomass, and, particularly, nutrients brought in from the soil bed.

The termitarium soil bed revealed much higher levels of available phosphorus, potassium, sulphur, iron, and trace iron than the workings mix. Because the workings contained a combination of decomposed paper and soil brought up from the bed, it is difficult to trace the origin of the nutrients found therein. Thus, the amount of soil brought in by the termites was unquantifiable. Nonetheless, the majority of nutrients found in the workings must be the product of decomposed paper and decomposed wood. This is because the soil beds originally contained only building soil (yellow sand) and small amounts of mulch and humus on the top. The only materials added, since that time, were wood. Hence, the nutrients in the bed would have accumulated as a result of wood decomposition. It is uncertain, then, how much nutrients a given mass and type of paper may contribute to the soil-nutrient economy when decomposed by termites. What can be said from the analyses is that the nutrients found to be in relatively high concentrations in the workings (and in surplus to the control mix) are, in fact, present in the glossy paper, newspaper, and office paper types. This was especially seen in glossy paper (Table 10).

Apart from macro- and micronutrients, the workings remain a source of organic carbon and calcium carbonate, which may be used to increase the fertility of nutrient-deficient soils and increase the pH of acidic soils, respectively.

As the acidity of a soil increases, the availability of major nutrients decreases (Atwell *et al.*, 1999). Acid soil infertility is a major form of land degradation in Australia, and one

method used in agriculture to neutralize acidic soils is the application of calcium carbonate (lime) (Atwell *et al*., 1999). Calcium carbonate is used as a filler in the paper industry, and may reach very high concentrations in material such as magazine (McKinney, 1995). This is perhaps the main contributor to the high pH of the workings. The glossy paper, office paper, and newspaper revealed calcium concentrations of 57.3 g/kg, 39.1 g/kg, and 1.9 g/kg, respectively. The resulting high pH of the workings gives credence to the material being suitable for mixing with acidic native soils.

Further research is recommended into the nature of termite remains when fed waste paper. It was not possible to use a nutrient-deficient soil bed in the termitarium trials, but if this had been done, it might have revealed more accurate amounts of nutrients left behind from the paper alone and for a given mass. Further trials investigating optimal paper-moisture concentrations and different physical states of the paper (i.e. shredding) would aid in finding optimal decomposition conditions. As *M. darwiniensis* and *C. acinaciformes* are known to metabolise and eliminate the trace levels of toxic xenobiotics found in paper and printing inks (Haritos *et al*., 1993; 1994), these termite remains should also be analysed for toxicity and levels of these compounds before a decision is made to utilise the material.

4.3 Field Trial (Alice Springs)

The large-scale termite feeding stations designed by John French were effective in focusing feeding activity of the local subterranean termite population in Alice Springs, but to varying degrees. This variability was dependent on environmental surroundings such as the degree of termite activity seen in mud-tubes and workings on dead and living plant material, the amount of material being decomposed at the site, and the concentration of trees and grasses utilized as a heat buffer. Ultimately, the main physical factors that limited the attractiveness of the drums and bags to termites and decomposition of the paper were temperature and moisture (Krishna & Weesner, 1969). Although decomposition rates were relatively low, elements of this trial may contribute to further research into bioconversion of waste paper by termites in areas where recycling is not commercially feasible.

Prospecting for wood-feeding termites was relatively easy (i.e. visually and spatially), and up to twenty active sites were found along the approximately 500-metre roadside. The most active sites were chosen according to available wood, termite mud-tubes and workings, and any tree-mounding activity, typical of *C. acinicifformes*. *Microceratermes* sp. was initially found in two of the 10 sites, cohabiting with *Shedorhinotermes* sp. at one site and *C. acinaciformes* at another. Cardboard indicators indicated that *Microceratermes* sp. did not enter the drums, perhaps because it is not known to display a preference for particular vegetation types (Krishna & Weesner, 1969). *Shedorhinotermes* sp. established in three drums situated at sites containing dead wood. These were very active, with only three bags in total showing no activity. In fact, the drum most successful in decomposition and revealing the most termites in the bags was drum #9, containing *Shedorhinotermes* sp. This supports the literature, which states that, after *Mastotermes* and *Coptotermes*, *Shedorhinotermes* is Australia's most destructive genus in regards to the damage caused to timber, buildings, and trees (Creffield, 1996). Six sites revealed *C. acinaciformes*. These were the most visually obvious sites in regards to termite activity, due to mounding (at four sites) and large amounts of termite mud-tubes and workings on dead and living trees. Sites 1, 2, 3, and 5 displayed this mounding and the drums became very active, as indicated by the cardboard indicators. Thus, prospecting for candidate sites to set up feeding stations may be more dependent on the degree of evident termite activity at the site than the particular species found.

The most successful sites, in terms of high level of activity and willingness to enter the drums, were those with shading from trees and the highest concentration of grasses (i.e. buffel grass). This provided a buffer for heat and moisture loss, the two most important factors affecting activity of termites (Krishna & Weesner, 1969). This relationship between vegetation shading and termite activity was also experienced in northern Australian tropical savanna with paper baits exposed to the soil surface (Dawes-Gromadzki & Spain, 2003). Thus, surrounding vegetation must also be taken into account when gauging the capacity of termite activity at a site.

Fungal hyphae were observed growing on the moist paper of the 'untouched' bags on drums #7 and #8, and to a lesser extent on others. Many termites show a preference for wood that has been altered by fungi which aid in the digestion of cellulose. However,

some fungi produce substances that are toxic to termites (Krishna & Weesner, 1969). Although the fungus has not been scientifically identified and proven to be toxic, it is noteworthy in regards to conditions required for decomposition of waste paper by termites.

The feeding stations were attractive to termites insomuch as they provided an enclosed environment with a favourable food source (i.e. untreated pine). Some problems were experienced, however, in the application of this design with plastic bag attachments in Alice Springs.

The thick plastic bags were employed in an attempt to create containers which may hold the termite workings and be easily removed for transport and application to gardens, etc. In total, 75 % of the plastic bags were prospected by termites, but decomposition therein was relatively low. This is especially true given the 5-month trial period. The termites endeavoured to bring soil from the ground, through the drum, and into the bags. About half of the active bags, however, displayed a number of holes chewed through the bottoms in an effort to create direct access to the soil. This may have been due to lack of aeration in the bags, which is also important for termite foraging (Krishna & Weesner, 1969). It is therefore evident that increased rates of decomposition of paper in the field may require direct access between the paper and the subterranean environment.

The feeding stations were limited in attractiveness to termites given the ambient environmental conditions of Alice Springs, typical of central Australia. The climate of Alice Springs is arid, often with little or no rainfall and daily temperatures may vary by an average of 28°C between minimum and maximum (Bureau of Meteorology, 2006). Foraging of subterranean wood-eating termites is known to be influenced by varying air and soil temperatures, which are dependent on daily and seasonal weather patterns (Evans & Gleeson, 2001). The wool bag, soil, and buffel grass were employed to reduce this variability in temperatures and water loss. The drums were also watered once per month to provide adequate moisture. This suggests that intermittent feeding patterns may have taken place within the drums, and, points to the importance of buffering unfavourable conditions in the field.

In terms of the practicality of being able to obtain and utilise the decomposed material as a conversion product, another significant component was the soil placed in the top half of the drums. The drums that became active, particularly those with *C. acinaciformes*, displayed much movement and aeration of this soil. Upon completion of the paper trial, drum #2 was dismantled to observe internal decomposition and activity. This was done with great difficulty as the soil on the top half of the drum was dense and cemented by termite secretions. Therefore, although the soil would have decreased the internal temperature of the drums, perhaps another method should be employed that buffers environmental conditions, yet is easily removed to harvest remains and replace the cellulosic material.

There is much room for improvement in the infrastructure to cater for the environmental conditions required by subterranean termites in an effort to increase foraging behaviour. When these favourable conditions are met, environmental detractants are lessened and decomposition rates may increase.

John French originally designed the feeding stations to be applied in northern Queensland to attract *M. darwiniensis* (French, 1998). Here, temperature and moisture are at more favourable levels. French also suggested the concept of implementing these feeding stations to produce sustainable supplies of *M. darwiniensis* biomass to be harvested as a supplementary protein food-source for fish, pigs, poultry, and native animals housed in zoological establishments. *M. darwiniensis* is perhaps the best candidate for biogenic conversion of waste paper where it occurs north of the Tropic of Capricorn. Where this species does not occur, such as at Alice Springs, *Coptotermes* and *Shedorhinotermes* are perhaps the genera most able to decompose waste paper, due to their aggressive feeding habits and ability to decompose most wood types.

5.0 Conclusion

Termites are efficient at decomposing waste paper. Maximum decomposition rates are dependent on favourable environmental conditions. Optimal conditions are moderate temperature (32-34°C), high humidity (80-90% R.H.), suitable soil, and constant water

supply (Krishna & Weesner, 1969). These conditions were met in the termitarium. Environmental conditions fluctuate in nature, and foraging is restricted by seasonal and daily patterns. This was shown to be that case in the field evaluation performed in Alice Springs, Northern Territory. Further research is recommended into methods of buffering unfavourable conditions in feeding stations, where recycling and construction of an insectary is not economically feasible, and environmental conditions are extreme.

Paper that is physically and chemically closest to the termite's natural wood food-source, such as newspaper, was most preferred by *C. acinaciformes*, followed by glossy-coated paper and white office paper. Mixing newspaper with glossy paper increased the overall decomposition of samples. Saturation of paper was revealed to be a slight deterrent, but this was also a factor in increasing overall decomposition rates.

The termite workings left in the termitarium containers were found to contain nutrients of horticultural significance. Large areas of Australia are deficient in major nutrients (P, N, K and S) and trace elements (Cu, Zn, Mn and Mo) (Atwell *et al*., 1999). The material was deficient in nitrogen, but relatively high in phosphorus, potassium, sulphur, organic carbon, and trace elements copper, zinc, manganese, and iron. The workings, which revealed a pH of 8.18, may also be suitable for neutralising acidic native soils, contributing to the health and activity of soil biota. As the workings contained soil brought up by the termites in the trial bed, the nutrients were incorporated into the material produced from accumulated decomposed remains of paper (in the containers) and wood (from previous feeding).

Biogenic conversion of waste paper by termites leads to useful conversion products of organically rich, nutrient-containing material and termite biomass that is rich in essential fatty acids, proteins, and vitamins (Finke, 2002; Paoletti *et al*., 2003). Further research is recommended into the cost-effectiveness of building a termitarium to attain maximum decomposition rates in line with the possible market for conversion products. Further research is also recommended into levels of toxic xenobiotics left in the workings before a decision is made to utilise them in horticulture.

This technology could also be applied to *M. darwiniensis* where it occurs north of the Tropic of Capricorn in Australia, as recommended by French (1998), and because it is one of the largest and the most destructive termite species in Australia (Creffield, 1996).

Possible negative impacts of implementing this technology could include the spread of toxic xenobiotics from the paper industry via utilising the decomposed remains, accumulating undesirable levels of nutrients at a given site, and assisting in the further release of greenhouse gases. Termites may emit large quantities of methane, carbon dioxide, and molecular hydrogen into the atmosphere, especially in tropical areas (Zimmerman *et al*., 1982). Large amounts of waste paper continue to be disposed of in landfills. This is especially true for non-recyclable grades and most paper in areas where recycling is not economically feasible. If termites were not utilized to decompose the material, and the waste paper was disposed in landfills, then the same greenhouse gases will ultimately be released from the landfills (Pickin *et al*., 2002). Termites are also known to produce chloroform, although studies have shown that termites are not likely to be a significant global source (Khalil *et al*., 1990).

6.0 References

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Useful Web Sites

Beneficial Uses of Termites, Dr. Timothy Myles, University of Toronto.
http://www.utoronto.ca/forest/termite/benefice.htm

Online Termite Database
http://www.unb.br/ib/zoo/docente/constant/catnew.html