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Dealing with nitrogen in subtropical Australia: Seven case studies in the diffusion of ecotechnological innovation

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ABSTRACT

This paper describes seven case studies in which ecotechnological approaches are being used to reduce the discharge of nitrogen to the environment in three local government jurisdictions in the moist subtropical zone of eastern Australia. Both technical performance and factors relating to acceptance of the technologies are examined. Three of the technologies have survived early setbacks to achieve increasing acceptance. Composting toilets and reed beds (sub-surface flow wetlands) have achieved takeoff in the on-site wastewater context in the Lismore City Council area where the level of adoption (based on 2004–2005 figures) for both technologies was approximately 30% of newly approved systems. In both cases, the level of adoption has been favoured by local scientific studies which have confirmed claims regarding technical performance and by regulations which encourage the reduction of nitrogen discharge to the environment. Free water surface (FWS) wetlands are installed as polishing devices at three of the 10 sewage treatment plants (STPs) in Lismore and the adjoining Byron and Richmond River Shires. Early problems arising from inexperience at design, construction and management of these wetlands have been overcome as local familiarity has increased. This confidence has been a factor in the decision to support a major upgrade to the West Byron constructed wetland system and to install a further three wetlands locally.

A further two technologies each have one full-scale system in operation. A 24 ha multipurpose wetland regeneration project for effluent polishing and transpiration, acid sulfate soil management, wetland regeneration, and carbon sequestration, recently installed at the end of the West Byron STP treatment train, is reducing total nitrogen concentrations from approximately 4–1 mg/L. A landfill leachate treatment system incorporating pond, macrophyte zones, horizontal flow gravel filter and single pass sand filter is reducing NH_4-N and TKN concentrations by 95% and 84%, respectively.

The final two technologies described are associated with the reuse and/or treatment of municipal wastewaters. The annual crops hemp and kenaf have both exhibited high N uptake rates in irrigated crop trials. However, their short growing season has resulted in rejection as production crops at one STP in the Byron Shire. The recent realization that the perennial pasture grass *Setaria sphacelata* can perform the role of wetland macrophyte has given rise to the concept of the “wet-and-dry-land” cell. Still at the pilot stage, this ecotechnology may have application in areas with distinct wet and dry seasons.

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1. Introduction

Recent increases in energy prices and growing unease regarding the impact of greenhouse gas emissions on the global climate system have added to existing concerns about the impact of human activity on the natural environment and the ecosystem services which it provides. Numerous authors suggest that an important component of humanity's response to these crises would be the development and deployment of innovative human support technologies that are based on ecological principles rather than more traditional energy and chemical intensive approaches (Mitsch and Jorgensen, 2003; Todd et al., 2003; Reed et al., 1995). While there is a growing list of successful examples of ecologically engineered technologies that have the potential to move human societies towards a more benign relationship with Nature, the following questions arise: (1) is the current rate of diffusion of these innovations from the "laboratory to the marketplace" sufficient to offset the combined effects of population increase and business-as-usual practices on the environment? (2) if not, how can the rate of diffusion be increased? and (3) what are the factors which hinder or contribute to the rate of adoption and diffusion of environmentally benign technologies?

Taylor et al. (2005) describe innovation as a process consisting of four activities: *invention*, *adoption*, *diffusion* and *learning by doing* which overlap and feed back on each other. Rogers (1995) suggests that there are five attributes of an innovation which most affect its chances of adoption and subsequent diffusion. In the context of this paper these can be described as: (1) the degree to which the innovation is perceived to have a *relative advantage* over the approach that it supersedes; (2) the degree to which it is perceived to have *compatibility* with existing practices within the industry and with cultural norms within the community of potential adopters; (3) its perceived degree of *complexity* or difficulty to use; (4) its degree of *trialability* before a major commitment is made; (5) its *observability* or the degree to which existing installations are visible to potential adopters. In the context of environmental technologies *relative advantage* with respect to a number of criteria (e.g. initial and ongoing cost, reliability and predictability of performance, ability to meet certain regulatory requirements, etc.) is arguably the most important of these five attributes.

This paper is a reflection on more than a decade in which the authors have traversed the innovation pathway in the development and promotion of a number of ecotechnologies. The geographical context is three adjoining local government areas, Lismore, Byron and Richmond River located in the moist subtropical zone of the Australian state of New South Wales (NSW). This largely rural area is currently experiencing a rapid increase in population, giving rise to concerns regarding environmental impact. The Centre for Ecotechnology (CET) at Southern Cross University in Lismore engages in research and consultancy services in areas related to regional resource management and ecosystem protection. The approach of the centre to these issues is reflected in its motto "turning wastes into resources by closing cycles locally, visibly and elegantly". A major guiding principle has been the avoidance, where possible, of energy and chemical dependent processes in system designs. Inspiration for this approach comes from the emerging discipline of Ecological Engineering with its definition "... the design of sustainable ecosystems that integrate human society with the natural environment for the benefit of both" (Mitsch and Jorgensen, 2003). Many of the research and consultancy projects undertaken by CET staff and students in association with local companies and councils have been concerned with the protection of aquatic and marine environments from pollution by nitrogen.

In the last century, the quantity of nitrogen transferred from the atmosphere to the biosphere globally has doubled as a result of human activities such as fertiliser production and the increased use of nitrogen fixing crops in agriculture (Galloway, 1998). Much of this additional nitrogen passes through human settlements to pollute aquatic and marine ecosystems via "wastewaters" or as leachates and runoff from enterprises such as farms and landfills. Galloway (1998) makes the point that since 1950 the production of nitrogenous fertiliser has been directly proportional to global grain production. This suggests that, with a world population (and hence grain production) increase of a further 50% predicted by 2050, the creation of mobile, reactive nitrogen species on the planet will continue to rise.

Fig. 1 shows the processes by which nitrogen in an aqueous stream can be prevented from entering the natural environment. The first of these processes, source control, encapsulates two basic principles of waste management: (1) treat the

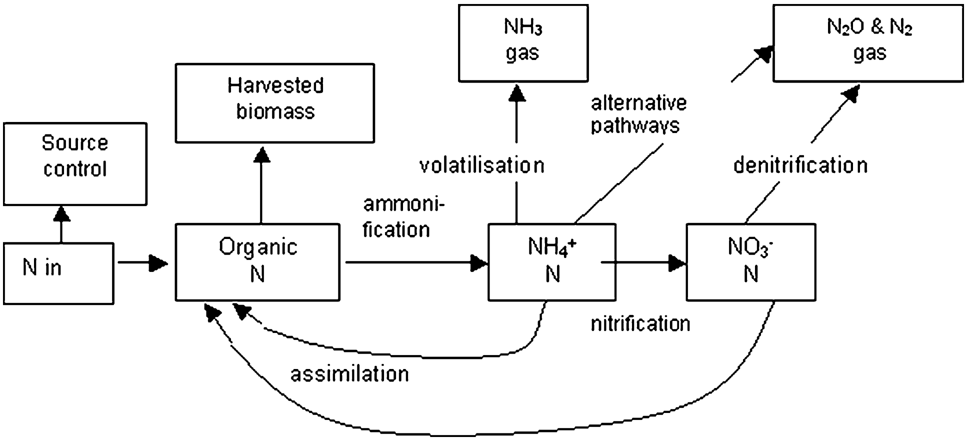

Fig. 1 – Nitrogen storages, transformations and exit pathways in aqueous environments (after Kadlec and Knight, 1996).

problem as close to the source as possible and (2) avoid diluting effluents. In other words, where possible keep nitrogenous material in a sufficiently solid or concentrated form to be subsequently utilised in some appropriate human enterprise such as agriculture. The urine separating toilet is a technology that exemplifies this principle (e.g. Kirchmann and Pettersson, 1995).

Crites et al. (2006) identify three generic device types that can be used for the natural treatment of effluents. These are ponds, wetlands and land application systems. In most wastewaters nitrogen exists in the reduced organic and ammonia forms (organic-N and NH_4-N, respectively) due to the ambient anoxic and anaerobic conditions that normally prevail in these environments (Fig. 1). Sequestration of nitrogen in organic form in crops irrigated with reclaimed water followed by subsequent harvest of the biomass is becoming increasingly common (Reed et al., 1995). A more novel example of this pathway is provided by the advanced pond system in which nitrogen is removed as algal biomass (Craggs et al., 2003). The dried algae can be used as fertiliser and soil conditioner. An exit pathway, available in waters with relatively high pH, is volatilisation as ammonia gas (NH_3). This pathway can become active in nitrogen-rich aqueous environments like waste stabilisation ponds subject to pH elevation resulting from algal photosynthesis. In free water surface (FWS) and sub-surface flow (SSF) wetlands it has been assumed that most of the nitrogen removal occurs via the two stage process of nitrification (requiring aerobic conditions and some alkalinity) and denitrification (requiring anaerobic conditions and a supply of organic carbon). Denitrification can also be a significant contributor to losses of N from irrigated land application areas. A number of possible alternative pathways for the transfer of ammonia-N to the atmosphere in oxygen depleted systems such as subsurface flow wetlands have been suggested by Tanner and Kadlec (2003).

The following case studies describe the development and performance of a number of ecosystem-like devices for the management of nitrogen which have been designed, built or studied by members, students and associates of the CET. An attempt is made to identify the cultural, technical, economic and regulatory factors which have either favoured or hindered the diffusion of each technology to potential adopters.

2. On-site wastewater management

In the early 1990s, a number of studies demonstrated that approximately 40% of domestic on-site wastewater management systems in the coastal zone of NSW were failing (Geary, 1992). In response the NSW Department of Local Government introduced a set of guidelines (DLG et al., 1998) which require all local Councils in the state to prepare an on-site sewage management strategy (OSMS) with requirements relevant to their particular geographic and climatic situation. The guidelines encourage councils to adopt an approach to land application area (LAA) sizing that not only takes account of the receiving soil's hydraulic capacity but also its ability to minimize discharge of nitrogen and phosphorus to ground and surface waters. Lismore City Council (LCC), with approximately 6000 domestic on-site systems in its rural areas, implemented an amended OSMS in 2003 after 4 years of trialling a draft strategy (LCC, 2003). The Strategy includes a model for sizing the system's land application area on the basis of hydraulic, total nitrogen (TN) and total phosphorus (TP) loadings. It assumes that each member of a household generates 4.2 kg of elemental nitrogen per annum. Households on allotments greater than approximately 2 ha and remote from waterways are permitted to release 15 kg of nitrogen per annum into the environment. This allowance is reduced for smaller allotments and where the land application area is closer than 100 m to a waterway. The model has been programmed onto a Microsoft Excel spreadsheet and is described more fully in McCardell et al. (2005). For a typical dwelling, with combined flush toilet and greywater sources served by a septic tank and trench in the clay loam soils typical of the region, the nitrogen loading is invariably the factor which determines the LAA size. Thus householders, especially those on small allotments, may have an incentive to reduce their nitrogen export loading.

2.1. *Source control by composting toilet*

Source control can be an effective approach to minimising the nitrogen load in the domestic aqueous waste stream. Quoting figures from German studies, Otterpohl et al. (2003) report that up to 90% of the total nitrogen in domestic wastewater has its origin in urine and faeces. As well as protecting the environment from excessive nitrogen loadings composting toilets use no water (an important fact in an area subject to extended dry periods) and create a resource which can provide a source of soil conditioning organic material and non-leachable but plant-available nutrients (Del Porto and Steinfeld, 1999). Consequently, the LCC design model allows a reduction in the design nitrogen loading by a conservative 70% and the design hydraulic loading by 32% in households served by a composting toilet.

Van der Ryn and Cowan (1996) cite the composting toilet as the technology that most epitomizes their five principles of ecological design. These are: (1) design solutions should be appropriate to their location; (2) account should be taken of the ecological as well as financial costs of a project; (3) the design should emulate the cyclic structure of natural systems; (4) the design of a project should evolve organically in conjunction with the community for whom it is being developed; (5) the finished project should make nature visible.

There has been considerable interest in composting toilets in the Lismore and surrounding areas for well over a decade (Walker and Davison, 2003; McCardell et al., 2005). Up to the end of June 2005, 394 units had been approved in the LCC area (Lismore City Council records). This figure equates to 6.5% of the total number of on-site systems in the council area and compares with a figure of approximately 0.5% for the state of NSW as a whole. Approximately 70% of these units are custom-built (i.e. not manufactured in a factory by mass production methods). Despite being designed to be insect proof it has been observed that many macro-invertebrates are sufficiently resourceful to find their way into the composting chambers of both manufactured and custom-built toilets, with the outcome being improved system operation and efficiency. These toilets therefore offer opportunities to study the phenomenon of system self-organisation that is described by

Table 1 – Treatment performance summary (as measured by percent reduction in concentration) from 32 studies on reed beds treating four types of wastewater (after Davison et al., 2005)

Wastewater type	Number of studies	HRT[a] (days)	BOD (% reduction)	TSS (% reduction)	TN (% reduction)	FC (log reduction)
Combined	8	8.9	92.5	88.7	60.2	2.5
Greywater	9	5.2	83.8	81.5	62.0	1.8
Laundry	3	6.1	61.2	82.7	62.4	0.8
School	8	11.5	74.9	79.3	38.1	1.7

[a] Mean hydraulic residence time.

Mitsch and Jorgensen (2003) as *the property of systems in general to reorganize themselves given an environment that is inherently unstable and non-homogeneous*. One of the species that has colonised a number of local composting toilet chambers is a native cockroach in the family *Balberidae* (Garry Scott, Compost Toilet Systems, Mullumbimby, personal communication). It has been observed that once a population of these cockroaches is established in a composting chamber, it plays a valuable role in physically moving, aerating and decomposing the deposited organic material, ultimately improving the rate of decomposition and compost stabilisation. The physical activity of the cockroaches can reduce the operational requirements of the systems by slowing the rate at which the heap builds up under the delivery chute. Breeding populations of these roaches have now been successfully introduced into a number of composting toilet systems (Scott, personal communication).

2.2. *Horizontal subsurface flow wetlands (reed beds)*

The use of secondary treatment in on-site wastewater management systems is becoming increasingly common in Australia. The relevant standard AS/NZS, 1547:2000 defines a secondary treated effluent as one in which total suspended solids (TSS) and biochemical oxygen demand (BOD) are less than 30 and 20 mg/L, respectively. There are a number of technologies capable of achieving these water quality levels with domestic wastewater. These include: aerated treatment systems, horizontal subsurface flow wetlands or reed beds, single pass sand filters (SPSF), and recirculating sand filters. Of these four, the reed bed has the advantage of being able to remove a significant proportion of the nitrogen load and of being totally passive (no requirement for power). In the mid 1990s, a small group of local enthusiasts and academics started to build and monitor reed beds. Table 1 summarises the results of 28 separate studies on the performance of 13 reed beds treating four different kinds of effluent (Davison et al., 2005). From the perspective of TN reduction the greywater systems showed the highest removal rate (62% reduction in concentration in an average of 5.2 days). This is probably because a large proportion of greywater nitrogen is associated with settleable food particles from the kitchen sink. The low TN removal rate in the school wastewater was related to the fact that the low ratio of BOD (average 110 mg/L) to TN (average 180 mg/L) concentration reduced the potential for denitrification.

These results have been used to generate first order models for predicting approximate attenuation of BOD and total nitrogen (TN) as a function of hydraulic residence time (Davison et al., 2005). These are plotted in Fig. 2. These reed bed performance models are incorporated into the models used by local councils in the region so that system designers can easily ascertain the effect of reed bed size on land application area size.

One of the long-term operational limitations of reed beds is the tendency for the interstices of the media to become clogged with organic solids, particularly if primary treatment is poor and an excessive solids loading is delivered to the entrance zone. Observations in a number of reed beds have highlighted how the process of self-organisation can occur in these ecological systems in order to counteract the process of clogging. Initial observations of a bed receiving greywater with high concentrations of solids, oils and grease found that after 9 years of operation a layer of humic earth-like material was present on the surface of the bed while the subsurface gravel was relatively clean and free of clogging material. Further investigations demonstrated that the bed had been naturally colonised by three species of earthworm, with the population of one in particular, *Perionyx excavatus* (Indian Blue), numbering in the thousands of individuals per square metre in the zone below the water surface (Davison et al., 2005). A mesocosm experiment demonstrated that the worms actively translocate clogging organic material from the gravel interstices and excrete it onto the bed surface above the water line, thereby prolonging the useful life of these systems (Davison et al., 2005). Investigations in a number of other reed beds in the region have identified a total of six species of worm, five of which are classified as epigeic feeders, that commonly colonise reed beds. In terrestrial situations epigeic worms ingest mainly surface organic material and very little mineral soil.

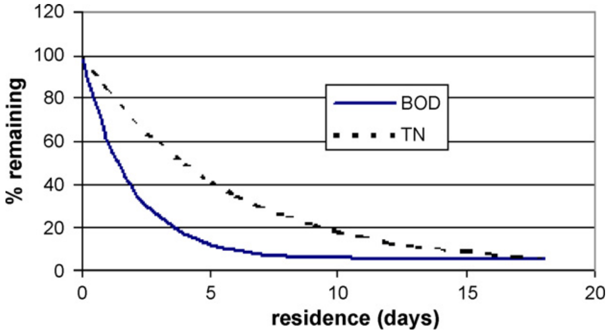

Fig. 2 – Predicted percentage of pollutant concentration remaining vs. residence time in reed beds treating domestic wastewater (*source*: Davison et al., 2005).

One problem associated with the transfer of reed bed technology has related to the quality of work on the part of installers. This has been partly overcome by running workshops and technical tours to highlight the good and bad points of existing systems. There has been a major issue in relation to the use of flexible membranes to line the beds. A number of these have been punctured by macrophyte roots and in one case a tree root had invaded a bed. The problem has been overcome by developing a purpose-built semi-rigid rotationally moulded medium density polyethylene (MDPE) tub approximately 3 m × 2 m × 0.65 m deep which is manufactured locally. The secondary treatment needs of a typical household are usually met by a reed bed system consisting of two or three of these tubs. This simple technological development has substantially increased the level of confidence that local regulators have in the technology and this has played a key role in its successful adoption and acceptance in the region.

3. Centralised wastewater management

In Australia, the disposal of secondary treated municipal wastewater to surface waters has been a traditional engineering practice that has led to widespread environmental impacts, particularly in estuarine and marine waters where nitrogen inputs favour algal bloom formation leading to oxygen depletion and associated changes in ecological structure (Eyre and Pont, 2003). The disposal approach has fallen out of favour over the last decade, with more environmentally sound strategies now being encouraged by regulation and policy development. A four-fold strategy developed in the 1990s, based on the National Water Quality Management Strategy (ANZECC and ARMCANZ, 1994), includes: (1) gradual introduction of Biological Nutrient Removal plants which has resulted in higher technology and treatment performance but increased capital and maintenance costs; (2) encouragement of wastewater reuse, mainly in agricultural irrigation schemes; (3) ecosystem-based treatment devices such as constructed wetlands and larger wetlands rehabilitated from agricultural land use.

3.1. *Free water surface (FWS) wetlands*

Many first-generation Australian constructed wetlands were designed and built during the early 1990s with the limited knowledge available at the time. Consequently a number of common problems developed in relation to maintenance of aquatic plant health, hydraulic management, and operation and maintenance issues. The poorer than expected effluent quality and high operating costs have led to a level of disappointment with the technology amongst regulators and sewage engineers. FWS wetlands installed at the sewage treatment plants (STPs) at South Lismore and the neighbouring town of Casino in the Richmond River Shire in the early 1990s experienced effluent quality compliance violations, and the respective councils commissioned rehabilitation work. One of the authors (Pont) undertook an initial assessment followed by work proposals, then a weekly regime of inspections, liaison with STP operators, physical planting, and weed control. Rehabilitation of both wetlands proceeded broadly in parallel, with lessons learned in one wetland being applied to the other.

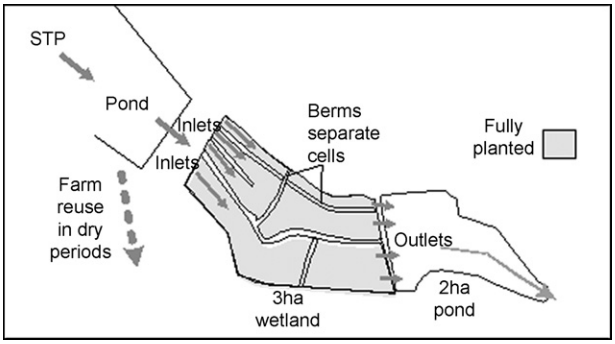

Fig. 3 – Casino wetland layout.

3.1.1. *Casino free water surface wetland*

The Casino wetland of 3 ha receives effluent (about 2.5 ML/day) from a trickling filter plant with added aeration tanks followed by a 4 ha pond (Fig. 3). The wetland was originally designed and built in about 1990 to operate at a constant depth of 200 mm, regulated by weirs of gravel that, although designed to be permeable, were causing effluent to back up, increasing the water depth to about 400–500 mm and leading to the ultimate dieback of wetland vegetation. The wetland was drained in early 2000 and replanted over 2 years mainly with *Typha orientalis* and *Bolboschoenus fluviatilis*. The slightly uneven cell floors were generally left unchanged. The original inlet structures were single pipes to individual cells which introduced inflowing wastewater in concentrated jets, leading to short-circuiting, plant dieback, and scouring of sediments, while outlets were shallow flows over the gravel weirs. Inlet structures of "perforated pipes" were installed across the heads of the inlet cells to distribute effluent and prevent scouring flows, along with multiple outlet pipes in the virtually impermeable gravel berms to encourage flow spreading and optimal contact with plant surfaces. Average operational depth is now 100–200 mm, with periodic drying of alternating cells by closing of inlet valves. The hydraulic residence time (HRT) of wastewater in the vegetated wetland cells is generally less than 1 day. By early 2004, the Casino wetland had reached full vegetation cover with a substantial litter layer.

The main management tool is the alternate application of effluent to the three flowpaths on a seasonal basis. Three months of application to two of the flowpaths, followed by 1-month drying, has been found sustainable and effective in oxidising accumulated wastewater residues and maintaining plant health. Operators have been successfully trained in assessment of plant health and have proven capable of effectively managing water levels in order to maintain vegetation vigour and cover.

Fig. 4 presents mean effluent TN concentrations from the Casino wetland system for each year over 8 years (pre-rehabilitation to present). It is thought that the addition of aeration to the STP in about 1998 resulted in better nitrification in the treatment plant, with subsequent denitrification in the shallow unvegetated ponds from 1999 to 2000. The rehabilitating wetland began to increase denitrification in 2001,

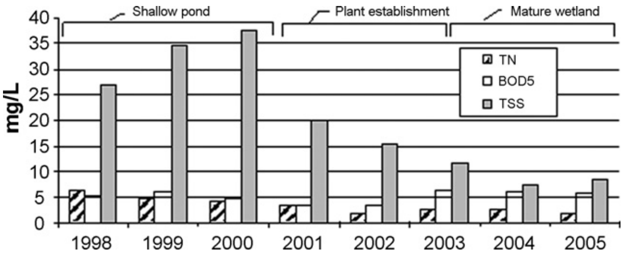

Fig. 4 – Mean annual outlet concentrations of TSS, TN and BOD$_5$ at Casino, 1998–2005 based on bi-weekly compliance monitoring.

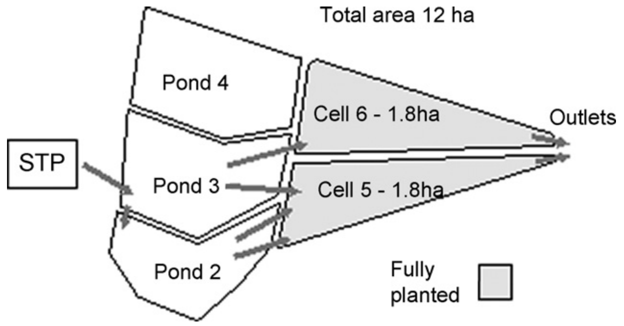

Fig. 5 – South Lismore FWS constructed wetland layout.

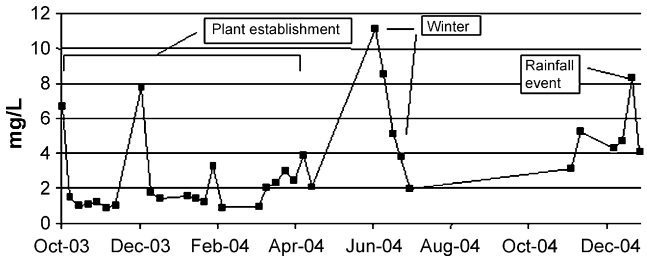

Fig. 6 – TN outlet concentrations at South Lismore STP, 2003–2005.

with consequent declining TN concentrations as the wetland matured. Mean TSS concentrations declined similarly over the 4-year period following the beginning of rehabilitation (37 mg/L in 2000 to 7.3 mg/L in 2004), while BOD$_5$ remained at about 5–6 mg/L throughout.

3.1.2. *South Lismore free water surface wetland*

The South Lismore STP receives flows of 3.5–20 ML/day from 20,000 pe and consists of a trickling filter system followed by a 12 ha pond–wetland system. The 12 ha area (Fig. 5), originally intended to be a six-cell FWS wetland system, was added to the STP in 1994–1995. However, due to deep depressions in cell floors, outlets being positioned too high for effective drainage, accumulation of organic sediments, and excessive numbers of waterfowl, early macrophyte plantings failed and the system came to resemble a series of ponds. The triangular shape of Cells 5 and 6 also presented hydraulic difficulties as velocity and depth both increase towards the outlets. The rehabilitation work in Cells 5 and 6 consisted of 2 years of preliminary observations and trials of plantings and flow changes, followed by dry season drainage and earthworks to address unfavourable slope and lack of drainage capacity. Cell 5 work began in 2002, and Cell 6 in 2003. The outlets were lowered by 900 mm. The author (Pont) visited weekly, carrying out the same operations as at Casino, i.e. working co-operatively with STP operators on flow management, ongoing trials of wetland plant species, weed control (small-scale application of herbicide to targeted weeds in the early phase), and protection of core plantings against waterbird damage. Wire netting cages were used on core rhizomatous plants in this case to exclude waterfowl that pluck seedlings from the sediment. The objective was the creation of a healthy, diverse, carbon-rich vegetated ecosystem as described by Wetzel (2001) who states that the most effective wetland ecosystems “are those that possess maximum biodiversity of higher aquatic plants and periphyton associated with the living and dead plant tissue”.

Fig. 6 presents the total nitrogen record from the earliest available compliance data, in October 2003 when the wetland was established and beginning to mature, to early 2005. TN concentration is low in the early ‘uptake phase’ of wetland establishment when plants and soils are assimilating nutrients in rapidly growing stems and roots, with background denitrification probably slowly increasing in efficiency. TN spikes occurred in winter and during rainfall events when flows increased from dry weather rates of 3.5–20 ML/day or more.

A 1-month trial was conducted on Cell 5 in November 2003. Table 2 shows the effect of passage through the planted wetland cells. pH drops from its elevated level of 8.6 down to 7.6. The TSS resulting from algal biomass accumulated in the pond cell is reduced from 74 to 1.8 mg/L in the wetland while BOD drops from 9.4 to 0.7 mg/L. TN continues to decrease in the planted wetland cell, falling from 5.4 to 1.0 mg/L.

3.2. *Multipurpose wetland restoration*

Byron Bay is a coastal town to the east of Lismore with a major tourist industry and a history of serious environmental

Table 2 – Cell 5 South Lismore STP, influent and effluent concentrations, November 2003

	pH	TSS (mg/L)	BOD$_5$ (mg/L)	TP (mg/L)	TN (mg/L)	NH$_4$-N (mg/L)	Faecal coliforms (cfu/100 mL)
Wetland inlet	8.6	74	9.4	2.8	5.4	0.7	1225
Wetland outlet	7.6	1.8	0.7	0.2	1.0	0.02	465

Source: Lismore City Council monitoring; 1-month trial; daily sampling excluding weekends: $n = 20$.

problems caused by effluent disposal, wetland destruction, and acid sulphate soil disturbance. In response to these problems, more than 500,000 *Melaleuca quinquenervia* trees were hand planted between 2001 and 2004 in a 24 ha effluent reuse wetland which is irrigated with tertiary treated sewage at a rate of up to 8 mm/day. Its primary functions are: (1) effluent polishing and transpiration; (2) acid sulfate soil management through water table control; (3) wetland regeneration, to increase ecological integrity; (4) carbon sequestration, through biomass and peat production (Bolton, 2004). One of the core aims of Byron Bay's sewage management strategy is to ensure that there is no net increase in nitrogen input into the local Belongil Estuary as a result of increased sewage flows. Consequently nitrogen dynamics were an important consideration in the associated study. The 1.5 m deep peat soil, which accreted during the last 6000 years from organic material deposition from a previous natural *M. quinquenervia* wetland, was found to be a major nitrogen sink, containing 15,600 kg of nitrogen per hectare in the top 50 cm of the peat layer. Thus an important research question was "will the peat liberate nitrogen to the effluent, causing nitrogen contamination of the estuary?" It was found that less than 1% of the nitrogen was in plant available form, suggesting that the peat retained rather than liberated nitrogen. To more directly assess the research question, nitrogen concentrations were analysed in the influent (fortnightly), groundwater (quarterly in 35 locations), and drains (quarterly) during the first 3 years of application. Fig. 7 shows that total nitrogen concentrations decreased throughout the treatment train, from an average of >4 mg/L in the influent to <1 mg/L of TN (mostly in organic form) in the outlet of the drain.

3.3. *Agricultural reuse of municipal wastewater*

While constructed wetlands are essentially an environmental protection measure, they do not make use of the water and nutrients for human purposes. Land application of treated effluent is increasingly being investigated and practised as a reuse option. The major issues most likely to present difficulties with this approach are excessive nitrate leaching and salinity (Bond, 1998). In the high rainfall region of north eastern New South Wales, salinity is not likely to be a significant problem for crops due to leaching of salts, especially during the summer and autumn periods of very high rainfall. Nitrate leaching on the other hand may threaten the quality of groundwater and ultimately exacerbate eutrophication of waterways.

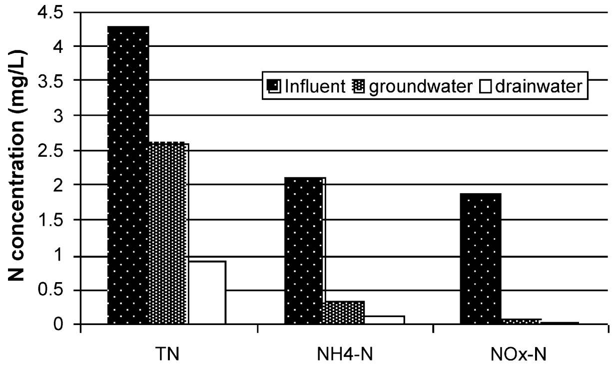

Fig. 7 – Average nitrogen concentrations and speciation in influent, groundwater and drainwater in the Byron multipurpose wetland from 2001 to 2004.

Table 3 – N input via effluent application and N uptake through biomass sequestration during the growth cycle of kenaf (130 days) and hemp (110 days) (McKenzie, 2004)

	N input via effluent (kg N/ha)	N uptake in biomass (kg N/ha)	N input from soil reserves (kg N/ha)
Kenaf			
0 mm/day	0	150	150
2 mm/day	56	196	140
8 mm/day	223	311	88
16 mm/day	445	509	64
Hemp			
0 mm/day	0	147	147
8 mm/day	202	239	37

Bangalow is a rapidly growing village in the Byron Shire with a small sewage treatment plant servicing the village. It is anticipated that sewage flows will increase from current levels (around 250 kL/day) to 600 kL/day within the next 15 years. As part of the proposed upgrade of Bangalow's sewage treatment infrastructure, Byron Shire Council purchased a 32 ha parcel of land directly adjacent to the sewage treatment plant to trial effluent irrigation of agricultural crops with a view to reducing dry weather discharge to local waterways. The local soil, a red Ferrosol, high in aluminium and iron oxides, is well known for its high phosphorus retention capacity, however, it has little nitrogen retention capability leading to concern about nitrogen leaching to groundwater. In order to investigate nitrogen dynamics two annual fibre crops – kenaf (*Hibiscus cannabinus*) and hemp (*Cannabis sativa*) – were planted on approximately 1 ha of the site and irrigated with secondary treated effluent (average N concentration 14 mg/L) via pressurised dripper lines at rates of 0, 2, 8 and 16 mm/day. Nitrogen concentrations in effluent and plant biomass of the two annual fibre crops were monitored. Both crops showed extremely high uptake rates with the most heavily irrigated kenaf plot extracting N at a rate of over 500 kg/ha during its 130 day growing season (Table 3). In all six trial plots the uptake of N by the crop exceeded the amount applied, with the difference being supplied by drawdown on soil N reserves. While the N removal capacity of these annual crops is high, their short growing season makes them unsuitable for year round effluent reuse and Byron Shire Council is now pursuing reuse options with perennial plants.

A second crop trial is being conducted at Mullumbimby, also in the Byron Shire. This trial is exploring the reuse potential of the naturalised pasture species *Setaria sphacelata*, a clumping grass which grows to 2 m, is attractive to cattle and is suitable for baling as hay or straw. Setaria has the advantage of being a perennial crop with a 9-month growing season in the local climate. In this instance secondary treated sewage was applied to the Setaria plots at two TN concentrations (10 and

Table 4 – Nitrogen uptake from effluent with two TN concentrations by Setaria under two harvest regimes (unpublished data)

N concentration (mg/L)	Harvest interval (kg/ha day)	
	1 month	3 months
10	0.83	0.1
25	3.32	1.8

25 mg/L). Under a monthly harvesting regime the Setaria crop took up nitrogen at a daily rate of 3.32 kg/ha (Table 4) while releasing only 0.046 kg/ha to downward drainage. The trials, carried out under optimum growing conditions, indicate that Setaria may be capable of an annual TN removal rate of up to 500 kg/ha.

An additional useful property of Setaria is its capacity to tolerate saturation and inundation for long periods. When it was noticed that this species had colonised a disused wetland cell at a local sewage treatment plant the cell was put back into operation and a 2-month trial was conducted with the cell running at a depth of 12 cm and a residence time of 1.5 days. The cell yielded removal efficiencies for BOD, faecal coliforms and TN comparable to those obtained with standard wetland plants.

3.4. *Wet-and-dry-land cell*

Large-scale reuse of treated sewage is logical and laudable but can be impractical in high rainfall areas such as the subtropics where deficit irrigation is mandated. The realisation that Setaria can perform well as both an agricultural reuse crop and wetland macrophyte has raised the possibility of creating cells that can perform either of these functions according to season. A suitably engineered cell planted to Setaria could be operated as a wetland in the rainy season to polish effluent prior to discharge to the environment. In the dry season it could function as a conventional reuse crop, turning water and nutrients into hay. A pilot scale trial is currently under way to accurately assess the pollutant removal rates of Setaria cells in wetland mode. *Phragmites australis*, a wetland plant that copes well with unsaturated soils and is attractive to cattle is also being trialled.

4. Landfill leachate

Leachate from solid waste landfills is formed by rainfall and runoff water percolating through the waste material. Various contaminants enter the leachate solution as it moves through the waste pile. As a result of the decomposition of organic wastes, landfill leachate tends to contain very high concentrations of ammonia-N (McBean and Rovers, 1999). Leachate from Lismore City Council's Waste Facility generates leachate flows averaging 40 kL/day with ammonia-N concentrations as high as 800 mg/L. The Waste Facility site has very little land available for irrigation but is adjacent to a sewage treatment plant. One option for dealing with the leachate ammonia problem was to nitrify the ammonia-N and to discharge it into the anaerobic, carbon-rich raw sewage at the front end of the sewage treatment plant to accomplish the denitrification step. As the capacity of ponds to reduce N concentrations is well documented (Maehlum, 1995) a leachate storage and treatment system consisting of a pond and vertical flow aerobic sand filter was designed with a view to reducing ammonia concentrations then nitrifying remaining ammonia prior to discharging it into the front end of the sewage treatment plant.

The system is depicted schematically in Fig. 8. Leachate from the landfill is intercepted in a trench and pumped to the storage pond (average depth ~0.7 m). It was decided at the design stage to improve pond hydraulic efficiency and potential for treatment performance by installing two macrophyte berms to create a three-cell structure. In order to protect the sand filter against clogging by algal biomass a gravel filter (later planted with wetland macrophytes in April 2006 after the study described below) was installed. The pond was completed in July 2004 and the sand filter in January 2005. Weekly grab samples were taken from the six points shown in Fig. 8 from 4th March to 24th June 2005. Pond pH varied from 7.8 to 9.8 with an average of 8.6. Water temperature fell from a high of 23 °C at the start of the trial to 15 °C at the final sample. Hydraulic loading rate to the sand filter averaged 94 mm/day.

Table 5 contains concentrations for selected water quality parameters through the treatment train. The reduction in concentration from point 1 to point 2 is a result of dilution of the leachate by stormwater runoff from the landfill surface. The system removal efficiencies in column 8 of Table 5 are therefore calculated with respect to point 2 adjacent to the pond inlet (Fig. 8). Ammonia-N removal by the entire pond-

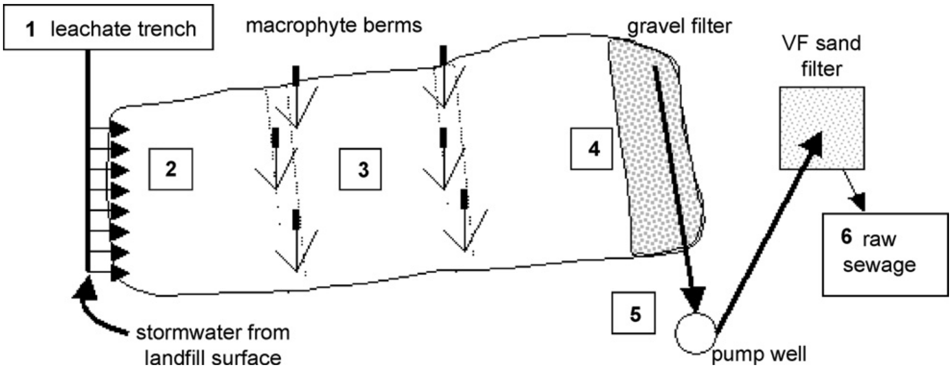

Fig. 8 – Leachate pond and vertical flow sand filter showing sampling points.

Table 5 – Selected average water quality concentrations (mg/L) in leachate treatment train from weekly grab samples 4 March to 24 June 2005 (*n* = 15, unpublished data)

	(1) Leachate trench	(2) Pond nr. inlet	(3) Mid pond	(4) Gravel filter inlet	(5) Pump well	(6) After sand filter	% removal efficiency
TKN	306.7	75.2	54.7	47.0	40.8	12.0	84
Ammonia-N	147.2	43.9	32.8	29.7	27.9	2.4	95
Nitrate-N	0.6	0.3	0.3	0.3	0.3	57.9	
BOD	69.3	42.0	38.0	45.3	26.9	15.3	64
Chlorophyll a	0.05	0.66	0.77	0.75	0.41	0.18	72

filter system is 95% and for the filter alone it is 91%. During the ~100 day passage through the pond TKN and ammonia-N concentrations declined by 18.2 and 14.2 mg/L, respectively. The corresponding figures for the 3-day passage through the gravel bed yielded reductions of 6.2 and 1.8 mg/L, respectively. The high pond pH suggests that the major N exit pathway there is via volatilisation. The reduction of Chlorophyll a in the gravel bed and the high reduction in TKN relative to ammonia-N indicates that filtration of algal biomass is the major N removal pathway in that device. Final concentrations of ammonia-N and TKN at 2.4 and 12.0 mg/L, respectively, are well below the compliance limits of 50 and 100 mg/L set by the NSW EPA.

5. Discussion—issues in technology transfer

This section examines the ecotechnologies described above from the perspective of their rate of diffusion into their respective adopter populations.

5.1. *Household–level technologies*

Table 6 shows annual figures for on-site wastewater management system approvals in Lismore for the 5 years to 30th June 2005 categorised according to major system components. Single pass sand filters are regarded locally as an ecotechnology as they are often loaded passively, in the typically hilly terrain, using a dosing siphon. In common with aerated systems they merely nitrify nitrogen and hence are mostly used to remove BOD and solids from greywater. Of most interest in Table 6 is the fact that systems containing an ecotechnology increased from 5% of the total approvals in 2001 to over 50% in 2005.

Composting toilets, already a relatively well-established approach to sanitation in the area by 2000, continued to perform well and, by 2005, had overtaken aerated systems in level of adoption (Table 6). Surveys indicate that the major motivation for adoption by early adopters was overwhelmingly for reasons of resource conservation and environmental protection (Pollard et al., 1997; Walker and Davison, 2003). The fact that the Lismore region consistently returns one of the highest proportions of “Green Party” votes in State and Federal Government elections indicates that a significant percentage of the local population places a high priority on these values. During the 1980s and early 1990s, when innovators and early adopters were experimenting with custom built composting toilet designs, local government regulators demonstrated a tolerant attitude and a small group of competent local contractors emerged. An important factor in gaining regulatory acceptance for these toilets was a study on the effect of seven composting toilets (six of them custom-built) on helminth survival during passage through the composting chamber. The study concluded that: “the systems are in fact working with respect to the destruction of parasites and commensals” and that the humus/end product was also most likely free of bacterial and protozoan pathogens (Safton, 1993). Partly as a result of this study, the NSW Health Department (1997) issued guidelines for the approval of composting toilets (including custom-built units) in the state. These guidelines formed the basis for the current national standard AS/NZS, 1546.2:2001.

From small beginnings in the late 1990s, reed beds increased steadily to 11 approvals in 2004 before taking off in 2005 with 31 approvals (Table 6). In terms of *relative advantage*, a number of factors support the reed bed as the favoured secondary treatment technology. Unlike the mechanically driven aerated system the reed bed does not require power, has

Table 6 – Annual approvals for on-site wastewater management systems in Lismore for 5 years to 30 June 2005

Technology	Year to					Overall total approved
	June 2001	June 2002	June 2003	June 2004	June 2005	
Aerated system	27	39	45	26	26	452
Single pass sand filter[a]	1	2	2	5	11	20
Reed bed[a]	1	7	8	11	31	80
Compost toilet[a]	16	19	36	20	29	394
All systems	364	400	597	140	104	6021
Ecotechnologies as % of total	4.9	7.0	7.7	25.7	51.9	

Source: Lismore City Council data.

[a] Indicates an ecotechnology.

relatively low maintenance requirements and is the easiest and cheapest secondary treatment option when failing disposal trenches signal the need for a system upgrade. Other factors are the reed bed's capacity to remove nitrogen and the growing acceptance of the technology by Council regulators, on-site system designers and system installers. Council support is based on extensive monitoring of early reed beds leading to the derivation of the predictive performance models shown in Fig. 2. An additional factor for Council has been the fact that early misgivings regarding quality of construction and the durability of flexible liners have been allayed by the introduction of the MDPE tubs in 2003. Workshops for system designers and installers and a growing familiarity with installation procedures have led to acceptance and understanding in these two key stakeholder groups.

Because of their perceived benefits as being natural technologies which promote resource conservation and reuse as well as environmental protection both reed beds and composting toilets are seen as attractive to members of an environmentally aware section of the community which contains the innovators and early adopters who launched the technologies locally. Jager (2006) also noted "social networks" and "problem awareness" among the mainly environmentally aware adopters of photovoltaic cells in the Netherlands as contributors towards the demand pull for that technology. The regulatory push contained in the guidelines which made nitrogen reduction desirable in Lismore has helped both composting toilets and reed beds to diffuse into sections of the wider community which are not necessarily motivated by concerns for the environment.

5.2. *Community–level technologies*

While the final decisions regarding the purchase of single household scale ecotechnologies rest with large numbers of individuals, decisions regarding large ecotechnologies like those described in Sections 3 and 4 of this paper are made by relatively few people in the purchasing organisation who may be strongly influenced by perceived attitudes of regulators and doubts about venturing into unknown territory. As noted by Rogers (1995) a successful "observable" example of an innovation will have a positive impact on the attitudes of potential adopters. Conversely perceived shortcomings will have a negative impact and be highlighted by proponents of the status quo.

Acceptance of FWS wetlands in Australia has been hampered by a number of factors including: (1) past failures of early generation wetlands; (2) contemporary emphasis on reuse of wastewater; (3) emphasis on high-cost (capital and maintenance) engineering technologies; (4) community and government perceptions of mosquito risk; (5) lack of understanding of ecosystem values of wetlands; (6) the need for understanding of the fill-and-draw concept, where rainfall events can be accommodated in FWS wetlands for a design period using controlled outlets with restricted flow rates, followed by slow outflow of highly 'polished' water. Despite these impediments three of the ten STPs in the Lismore, Byron and Richmond River Shires have FWS wetland systems which are now operating successfully. In addition a major FWS wetland upgrade project is currently underway at the West Byron STP. Concept designs have also been completed for three new FWS wetlands in the region, two of them in Byron Shire. The two FWS wetlands discussed in this paper have provided easily observable examples of successful systems. Many field visits have been conducted for local authority engineering and environmental health staff, as well as visitors from other regions, to inspire confidence in this ecotechnology. The wetlands feature landscapes of healthy green vegetation, visible and audible birds and frogs, and the sight of poor-quality influent transformed to clear and healthy looking outflow water. The high cost of some early generation wetlands has also now been rationalised and these systems can provide a cost-effective complement to treatment-reuse schemes or alternative systems where reuse is not practical.

6. Conclusion

The case studies described in this paper are all examples of ecotechnologies which are innovative in the Australian context and have a proven capacity to reduce the discharge of nitrogen from human settlements and activities to the environment. Most of these technologies have multiple pollutant attenuation benefits and several create a useful resource. Three of them, composting toilets, reed beds and FWS wetlands have achieved a certain degree of acceptance in the relevant adopter populations in the area under study. In each of these three cases early hiccups in the areas of design, construction and operation led to initial scepticism in the relevant adopter communities. In each case design or construction adjustments coupled with scientific investigations and extension activities led to a gradual increase in confidence. A changing regulatory environment also gave each technology a boost. In the case of reed beds and composting toilets this boost came in the form of incentives to reduce the load of nitrogen discharged from domestic on-site sewage management systems. In the case of FWS wetlands the boost arose from the need to reduce the concentrations of TSS and BOD resulting from algal blooms in stabilisation ponds. Additional reductions in TN concentrations provided a welcome bonus.

Two of the ecotechnologies, multipurpose wetland restoration and landfill leachate nitrification, each have one full-scale system operating successfully following pilot scale testing of the concept. In both cases unique circumstances made these two technologies economically attractive in their particular context. Having been proven in favourable circumstances both concepts will now be easier to transfer to other situations should the opportunity arise.

Effluent irrigated crop trials on kenaf and hemp indicated that both are capable of taking up large amounts of nitrogen. However, their short growing season and the need to replant annually has led to their rejection as reuse crops for municipal wastewater at Bangalow. The perennial pasture grass S. *sphacelata* has a high N uptake rate when harvested monthly and may have a future as a reuse crop. Its capacity to withstand flooding for extended periods and provide treatment indicates that it may have a future as a wet-and-dry-land cell macrophyte in the reuse and treatment of municipal and agricultural wastewaters under the distinct wet and dry seasonal conditions of a subtropical climate.

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