Biomass production and nutrient removal by tropical grasses subsurface drip-irrigated with dairy effluent

R. B. Valencia-Gica, R. S. Yost and G. Porter
Department of Tropical Plant and Soil Sciences, University of Hawaii at Manoa, Honolulu, HI, USA

Abstract
Effluent lagoons on dairy farms can overflow and potentially pollute adjacent land and associated water bodies. An alternative solution to effluent disposal is needed by dairy operators in island environments. An attractive win-win alternative is to recycle nutrients from this resource through effluent irrigation for forage grass production that minimizes environmental pollution. This study assessed biomass production and nutrient removal by, and high application rates to, tropical grasses that were subsurface drip-irrigated with dairy effluent. Four grass species – Banagrass (*Pennisetum purpureum* K. Schumach.), California grass (*Brachiaria mutica* (Forssk.) Stapf.), Stargrass (*Cynodon nlemfuensis* Vanderyst) and Suerte grass (*Paspalum atratum* Swallen) – were subsurface (20–25 cm) drip-irrigated with effluent at two rates based on potential evapotranspiration (ETp) at the site (Waianae, Hawaii) – 2–0 ETp (16 mm d⁻¹ in winter; 23 mm d⁻¹ in summer) and 0–5 ETp (5 mm d⁻¹ in winter; 6 mm d⁻¹ in summer). Treatments were arranged in an augmented completely randomized design. *Brachiaria mutica* and *P. purpureum* had the highest dry-matter yield (43–57 t ha⁻¹ year⁻¹) and nutrient uptake especially with the 2–0 ETp irrigation rate (1083–1405 kg ha⁻¹ year⁻¹ N, 154–164 kg ha⁻¹ year⁻¹ P, 1992–2141 kg ha⁻¹ year⁻¹ K). Average removal of nutrients by the grasses was 25–94% of the applied nitrogen, 11–82% of phosphorus and 2–13% of the potassium. Average values of crude protein (90–160 g kg⁻¹), neutral detergent fibre (570–620 g kg⁻¹) and acid detergent fibre (320–360 g kg⁻¹) were at levels acceptable for feeding to lactating cattle. Results suggest that *P. purpureum* and *B. mutica* irrigated with effluent effectively recycled nutrients in the milk production system.

Keywords: dry-matter production, nutrient uptake, dairy effluent irrigation, crude protein, acid detergent fibre, neutral detergent fibre, Hawaii

Introduction
Livestock and dairy production is often a concentrated animal-intensive operation, especially in an island environment. Such enterprises rely mostly on imported feeds to sustain their operation, which results in a tremendous influx and accumulation of nutrients and salts. These nutrients and salts can cause pollution of land and water bodies receiving the effluent. If the animal wastes are not re-utilized or exported, an open nutrient cycle is created in the milk production system. An attractive alternative for dairy producers is to apply the effluent for forage production to recycle the nutrients. Water and nutrients contained in dairy effluent may, in this way, be used to maintain or improve soil fertility and enhance forage production and quality. Reapplying animal effluent for forage production improves the efficiency of feed sourcing in dairy production and minimizes environmental pollution.

Various grasses and crops have been used to remove nitrogen (N) and phosphorus (P) from wastewater, for example, Stargrass (*Cynodon nlemfuensis*), Bermudagrass (*Cynodon dactylon* (L.) Pers.), Johnson grass (*Sorghum halepense* (L.) Pers) (McLaughlin et al., 2004; Adeli et al., 2005; Valencia et al., 2006) and Bahiagrass (*Paspalum notatum* Flügge) (Adjei and Rechcigl, 2002). Various forage systems have also been tested for the effects of dairy effluent or slurry application on nutrient removal, crop yield and forage quality (e.g. Macoon et al., 2002; Woodard et al., 2002).

Many tropical grass species have high biomass productivity, high nutrient removal potential, acceptable nutrient quality, persistence, tolerance to harsh environmental conditions, resistance to pests and diseases and ease of establishment (Takahashi et al., 1966; Duke,
1983; Pant et al., 2004). In Hawaii, *Pennisetum purpureum* produced up to 336 t ha
year
1 of green forage (Takahashi et al., 1966) or approximately 70 t ha
year
1 of dry matter, which is close to the 85 t ha
year
1 reported for *P. purpureum* that received 897 kg N ha
year
1 and was cut every 90 d under rainfall conditions of nearly 2000 mm per year (Vicente-Chandler et al., 1959). Given its high biomass and fixed carbon yield, *P. purpureum* was considered a promising feedstock for the production of metallurgical charcoal (Yoshida et al., 2008).

In recent years, there has been a renewed interest in the use of wastewater for growing crops or trees, or irrigating golf courses and turf grasses, all motivated by environmental objectives. One study on wastewater reuse conducted in Hawaii to remove N from secondarily treated domestic sewage effluent used *Brachiaria mutica* (Handley and Ekern, 1981). The relatively high consumptive water use (4 mm d
1) of this grass coupled with its fast and thick growth led to removal of about 69% of the effluent N at application rates of 475–2600 kg N ha
year
1. While some studies have investigated the use of subsurface drip irrigation for applying animal effluent (Stone et al., 2008; Cantrell et al., 2009), to our knowledge, no study has determined the potential of tropical grasses with subsurface drip irrigation. This study aims to assess the nutrient uptake, productivity and forage quality of four tropical forages (Figure 1). Augmented treatments (single replications) were *P. atratum* and *P. purpureum* with two replications each (Figure 1). Augmented treatments (single replications) were *B. mutica* (planted in January 2005) and *C. nlemfuensis* (planted at the beginning of the experiment) that also received two rates of effluent irrigation. Irrigation rates were based on the ETp, at the site: 2·0 ETp (average of 16 mm d
1 in winter and 23 mm d
1 in summer) and 0·5 ETp (average of 5 mm d
1 in winter and 6 mm d
1 in summer). From August 2004 to 2006, plots were irrigated accordingly through a subsurface (20–25 cm depth) drip effluent irrigation system. Forage yield, quality and soil chemical measurements were taken every 4–6 weeks during the 2-year experiment. The emphasis on temporal measurement and change permitted testing the hypothesis of no change in forage production, forage quality and soil properties over time with effluent irrigation. The number of replications was limited by land availability and to provide more robust data on repeated measurement of forage and soil properties over time. Additional information on experimental design and properties of dairy effluent was presented in an associated article (Valencia-Gica et al., 2010).

Materials and methods

Soil and climate

The experimental site was in Waianae (21°26’N/158°10’W), O’ahu, Hawaii, with a mean elevation of 2·4 m above sea level and average monthly ETp ranging from 5 to 21 mm d
1, varying with season. Rainfall is very low (150 mm annually), and the ETp is, thus, high compared with other locations on the island (Valencia-Gica et al., 2010). Rainfall, ETp and other weather data were collected using the Hobo (Onset Computer Corporation, Bourne, MA, USA) weather station installed at the site. The ETp was calculated using the Reference ETp Calculation and Software (Ref-ET v. 2.0), which uses the Penman equation (Allen, 2001). Monthly average ETp was obtained from the daily ETp calculated by Ref-ET.

The soil (Pulehu series) is a fine-loamy, mixed, semiactive, isohyperthermic Cumulic Haplustoll (Soil Survey Staff, 1972) and has 630 g kg
1 clay, 190 g kg
1 silt and 180 g kg
1 sand. Soil pH was already initially high (ranging from an average of 7·5–7·6 in July 2003), and with continuous irrigation with high pH effluent (ranging from 7·9 to 8·8), the soil pH further increased (ranging from an average of 8·3–8·5) after 2 years.

Experimental design

Twelve plots (which are the experimental units), each measuring 13·4 m
2, were planted in December 2003 to four tropical grass species that were observed to tolerate saline soil in Waianae (ECsaturated paste extract 1:2 soil-water ratio = 11–26 dS m
1). These grasses included: Banagrass (*P. purpureum* K. Schumach. cv. HA 5690), California grass (*B. mutica* (Forssk.) Stapf.), Stargrass (*C. nlemfuensis* Vanderyst) and Suerte grass (*Paspalum atratum* Swanlv cv. Suerte). *Pennisetum purpureum* is a variety of elephant grass. *Brachiaria mutica* is also called para-grass. These species are relatively untested in this high-solar-radiation environment, and it was a major objective to investigate how they performed with applications of dairy lagoon effluent in a tropical environment such as that in Hawaii. The grasses were allowed to establish to 95 to 100% ground cover with freshwater irrigation (30 min, twice a day) until July 2004.

Treatments were arranged in an augmented completely randomized design, patterned after the augmented block design developed by Federer (1956, 2005). Two rates of effluent irrigation were applied to *P. atratum* and *P. purpureum* with two replications each (Figure 1). Augmented treatments (single replications) were *B. mutica* (planted in January 2005) and *C. nlemfuensis* (planted at the beginning of the experiment) that also received two rates of effluent irrigation. Irrigation rates were based on the ETp, at the site: 2·0 ETp (average of 16 mm d
1 in winter and 23 mm d
1 in summer) and 0·5 ETp (average of 5 mm d
1 in winter and 6 mm d
1 in summer). From August 2004 to 2006, plots were irrigated accordingly through a subsurface (20–25 cm depth) drip effluent irrigation system. Forage yield, quality and soil chemical measurements were taken every 4–6 weeks during the 2-year experiment. The emphasis on temporal measurement and change permitted testing the hypothesis of no change in forage production, forage quality and soil properties over time with effluent irrigation. The number of replications was limited by land availability and to provide more robust data on repeated measurement of forage and soil properties over time. Additional information on experimental design and properties of dairy effluent was presented in an associated article (Valencia-Gica et al., 2010).

Micronutrients such as iron (Fe), manganese (Mn), zinc (Zn) and copper (Cu) were applied as foliar fertilizer beginning in April 2005 (Zn), November 2005 (Mn, Fe) and May 2006 (Cu) and continued for the duration of the experiment. The amount of micronutrients applied was adjusted every month.
depending on the results of the tissue analyses. Application rates were 337–562 g ha\(^{-1}\) month\(^{-1}\) for Zn, 56–337 g ha\(^{-1}\) month\(^{-1}\) for Cu, 337–562 g ha\(^{-1}\) month\(^{-1}\) for Fe and 562–1123 g ha\(^{-1}\) month\(^{-1}\) for Mn.

Nutrient content of dairy effluent was analysed periodically for estimating nutrient loads (Figure 2). At the \(2\times ET_p\) rate, cumulative nutrient loads were estimated at 1200 kg N ha\(^{-1}\) year\(^{-1}\), 620 kg P ha\(^{-1}\) year\(^{-1}\), 42 000 kg K ha\(^{-1}\) year\(^{-1}\), 2900 kg Ca ha\(^{-1}\) year\(^{-1}\) and 5900 kg Mg ha\(^{-1}\) year\(^{-1}\). At the \(0.5 ET_p\) rate, cumulative nutrient loads were estimated at 370 kg N ha\(^{-1}\) year\(^{-1}\), 190 kg P ha\(^{-1}\) year\(^{-1}\), 12 000 kg K ha\(^{-1}\) year\(^{-1}\), 850 kg Ca ha\(^{-1}\) year\(^{-1}\) and 1700 kg Mg ha\(^{-1}\) year\(^{-1}\).

**Grass harvesting**

Grasses were well established prior to a first harvest in August 2004. *Pennisetum purpureum* and *P. atratum* were initially harvested manually at 30 cm height (August 2004–October 2004), whereas *B. mutica* and

---

**Figure 1** Experimental treatment layout for tropical grasses drip-irrigated with dairy effluent, Waianae, O‘ahu, Hawaii.

**Figure 2** Nutrient concentrations in dairy effluent used for irrigation of tropical grasses in Waianae, O‘ahu, Hawaii, June 2004–August 2006.
C. nlemfuensis had been cut using a sickle mower at 8 cm height. From November 2004 to August 2006, all grasses were cut using a sickle mower at the same height of 8 cm to simulate expected dairy farmers’ practice. A 0.30 m border area on each side of the experimental unit was excluded from the yield calculations, resulting in an effective biomass harvest area of 9.29 m² per plot. The harvesting interval in the first year (August 2004–July 2005) was 27–29 d. This frequent harvesting was intended to provide high-quality forage. Growth progression of the grasses was measured from August to October 2005. During the second year (August 2005–2006), the harvesting interval was extended to 6 weeks based on the first year’s results and occurred after 42–44 d of growth. During each harvest, soil and soil-solution samples were also collected and analysed for nutrients (Valencia-Gica, 2007). Results on soil phosphorus changes were presented in an associated article (Valencia-Gica et al., 2010), and salinity changes will be discussed subsequently.

**Plant tissue analyses**

Subsamples were taken from each plot’s harvest and dried in a forced-air oven. Annual biomass production and nutrient uptake (average of the 2-year annual data) were calculated from the harvest and tissue nutrient data. Nutrient removal as a percentage of the applied nutrient was calculated as the nutrient uptake measured from the harvested biomass divided by the total nutrient applied annually.

The forage was analysed for macro- (N, P, K, Ca, Mg and Na) and micronutrients (Fe, Mn, Zn and Cu). Dried, ground samples (0–50 g, passed a 2-mm sieve) were dried ashed for 4–6 h at 500°C (Hue et al., 1997). Residues were dissolved in 25 mL of 1 M hydrochloric acid and the solution subjected to inductively coupled plasma-atomic emission spectrophotometry (Hue et al., 1997). Ashed samples were analysed for B by the azomethine-H colorimetric method (Wolf, 1974). Total N (0.25 g sample digested at 410°C) was analysed using a LECO CN-2000 analyzer (LECO Corporation, St. Joseph, MI, USA). Nitrate-N and NH₄⁺-N were auto-analysed using spectrophotometers (Gentry and Willis, 1988).

**Forage quality analysis**

Crude protein (CP) content was calculated from Kjeldahl N using the standard conversion: CP (g kg⁻¹) = N(g kg⁻¹) × 6.25. Acid detergent fibre (ADF) and neutral detergent fibre (NDF) were determined using the ANKOM Filter Bag Technique (ANKOM Technology Corp., Fairport, NY, USA) using 0.60 g of dried, ground tissue sample, extracted and re-dried at 102°C (2–4 h). Calculations were based on the following formula:

\[
\text{NDF or ADF (g kg}^{-1}\text{)} = \frac{W_2 - (W_1 + C_3)}{\text{Sample weight}}
\]

where \(W_1\) is the original bag weight (g), \(W_2\) is the dried weight of the bag with fibre after the extraction process, and \(C_3\) is the empty bag correction, which is the empty bag final oven dry weight divided by its original bag weight.

**Data analysis**

Data collection and analysis were carried out for 2 years (August 2004–2006). The emphasis on temporal measurement and change over time enabled testing of whether forage production, quality and soil properties could be maintained over time with effluent irrigation. The main treatments and interaction effects (Federer, 2005) on annual dry matter, nutrient concentration, nutrient uptake and forage quality data were analysed as unbalanced ANOVA using PROC GLM of SAS 9.1 software (SAS Inst., 2004). For the monthly data, best subset procedures were conducted using MINITAB 14.13 (Minitab Inc., 2004), and the main treatments, interaction effects and the change in yield and nutrient uptake and removal (reduced model) were analysed with repeated measures ANOVA using an autoregressive first-order covariance structure provided by PROC MIXED SAS 9.1 software (SAS Inst., 2004). Means were compared using the least significant difference using PROC GLM software (SAS Inst., 2004). To facilitate data analysis and discussion, the ‘time’ variable was used to refer to sampling dates that corresponded to the amount of effluent irrigation over time at each of the two irrigation rates.

**Results**

**Plant growth and dry-matter production**

Tropical grasses that received effluent irrigation exhibited relatively slow growth rates during the first 15–20 d after cutting, after which these species grew rapidly (Figure 3). The initial 27–29 d cutting resulted in high dry-matter production and generally good-quality forage (Figures 4 and 5); however, grasses had slow rejuvenation after 6 months of cutting at 27- to 29-d interval. Nonetheless, tropical grasses irrigated with effluent produced large amounts of dry matter. Brachiaria mutica receiving the 20 ET₀ effluent irrigation rate outyielded other grass species (\(P < 0.01\)), with dry-matter production reaching about 57 Mg ha⁻¹ year⁻¹ (Figure 4). Significant interactions on dry-matter yields were observed between grass species and time (\(P < 0.05\)) and between irrigation rate and time (\(P < 0.05\)). In general, higher dry-matter yields were
obtained in the June–October period (Figure 4), which corresponded to the period of highest seasonal ET_P with generally higher temperature and solar radiation (Figure 6). Warmer conditions coupled with adequate water supplied by effluent irrigation were highly favourable for high growth rates.

Tissue concentration and uptake of N, P and K

Tissue N concentrations of the grasses (Table 1) were low compared with the level adequate to support plant growth and development (280 g kg⁻¹) proposed for Bahiagrass (P. notatum) by Mills and Jones (1996). *Paspalum notatum* was chosen for comparison because of lack of information on adequate level to support plant growth and development specific for each grass species used in this study. The low N levels in the tissues, despite supplemental N fertilization in 2006, indicate high N requirement of these grasses to support plant growth especially with the relatively frequent harvesting and low cutting height. Nitrogen levels in the soil were also low (Table 2). Except for C. nlemfuensis receiving the 0·5 ET_P irrigation rate, the tissue P concentrations of all the other grasses were also mostly lower than the adequate level (40 g kg⁻¹) suggested for *P. notatum*. This despite the relatively high extractable soil P (Table 2) suggests the low plant availability of soil P because of possible precipitation with Ca (Valencia-Gica et al., 2010). Tissue K concentrations of the grasses exceeded the adequate level (180 g kg⁻¹), with *P. purpureum* having the highest (37·4–41·9 g kg⁻¹) suggesting luxury uptake of K, especially with the increased levels of soil K with effluent application (Table 2). Among the grasses, *P. purpureum* and *B. mutica* had usually the highest (P < 0·01) N, P and K uptake especially with the 2·0 ET_P irrigation rate (Table 1).
Figure 5 Forage quality indicators of tropical grasses drip-irrigated with dairy effluent, Waianae, O‘ahu, Hawaii, August 2004–2006.

Figure 6 Temperature, potential evapotranspiration and solar radiation, Waianae, O‘ahu, Hawaii, October 2004–August 2006.
Table 1  Average nutrient concentrations and annual total nutrient uptake of four tropical grasses receiving dairy effluent at Waianae, O'ahu, Hawaii, from August 2004 to August 2006.

<table>
<thead>
<tr>
<th>Irrigation rate</th>
<th>Grass species</th>
<th>Nutrient concentration</th>
<th>Nutrient uptake (kg ha(^{-1}) year(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N (g kg(^{-1}))</td>
<td>P (g kg(^{-1}))</td>
</tr>
<tr>
<td>2.0 ET(_p)</td>
<td>Banagrass (Pennisetum purpureum)</td>
<td>21.2</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>California (Brachiaria mutica)</td>
<td>24.8</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>Stargrass (Cynodon nlemfuensis)</td>
<td>21.0</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>Suerte (Paspalum atratum)</td>
<td>15.1</td>
<td>2.0</td>
</tr>
<tr>
<td>0.5 ET(_p)</td>
<td>Banagrass (P. purpureum)</td>
<td>19.7</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>California (B. mutica)</td>
<td>18.5</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Stargrass (C. nlemfuensis)</td>
<td>18.6</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Suerte (P. atratum)</td>
<td>15.2</td>
<td>2.4</td>
</tr>
<tr>
<td>LSD0.05</td>
<td></td>
<td>0.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Adequate level for Bahiagrass (Paspalum notatum)</td>
<td>28.0</td>
<td>4.0</td>
<td>18</td>
</tr>
</tbody>
</table>

\(^1\)Summer rate was 23 mm d\(^{-1}\), and winter rate was 16 mm d\(^{-1}\).
\(^2\)Summer rate was 6 mm d\(^{-1}\), and winter rate was 5 mm d\(^{-1}\).
ET\(_p\), evapotranspiration; LSD, least significant difference.
Table 2 Changes in properties of soil planted to tropical grasses receiving dairy effluent at Waianae, O’ahu, Hawaii, from August 2004 to 2006.

<table>
<thead>
<tr>
<th>Irrigation rate / sampling depth</th>
<th>Year</th>
<th>pH</th>
<th>N (%)</th>
<th>P (mg kg⁻¹)</th>
<th>K (mg kg⁻¹)</th>
<th>Ca (mg kg⁻¹)</th>
<th>Mg (mg kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2·0 ETₚ¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–15 cm</td>
<td>2003</td>
<td>7·50</td>
<td>0·1153</td>
<td>155</td>
<td>2229</td>
<td>5774</td>
<td>3109</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>8·38</td>
<td>0·0397</td>
<td>164</td>
<td>4199</td>
<td>5584</td>
<td>3051</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>8·35</td>
<td>0·0532</td>
<td>151</td>
<td>5443</td>
<td>5098</td>
<td>2966</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>8·48</td>
<td>0·0363</td>
<td>185</td>
<td>8031</td>
<td>4926</td>
<td>2963</td>
</tr>
<tr>
<td>15–30 cm</td>
<td>2003</td>
<td>7·63</td>
<td>0·0685</td>
<td>93</td>
<td>2972</td>
<td>5178</td>
<td>3144</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>8·03</td>
<td>0·0290</td>
<td>148</td>
<td>4599</td>
<td>5597</td>
<td>2932</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>8·22</td>
<td>0·0489</td>
<td>137</td>
<td>5480</td>
<td>5088</td>
<td>2890</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>8·29</td>
<td>0·0302</td>
<td>161</td>
<td>7695</td>
<td>4530</td>
<td>2776</td>
</tr>
<tr>
<td>0·5 ETₚ²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–15 cm</td>
<td>2003</td>
<td>7·53</td>
<td>0·0942</td>
<td>131</td>
<td>2178</td>
<td>5909</td>
<td>2991</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>8·19</td>
<td>0·0321</td>
<td>119</td>
<td>2694</td>
<td>5847</td>
<td>3025</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>8·23</td>
<td>0·0501</td>
<td>128</td>
<td>3140</td>
<td>5591</td>
<td>2904</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>8·34</td>
<td>0·0308</td>
<td>142</td>
<td>4462</td>
<td>5489</td>
<td>3032</td>
</tr>
<tr>
<td>15–30 cm</td>
<td>2003</td>
<td>7·55</td>
<td>0·0772</td>
<td>117</td>
<td>2318</td>
<td>6750</td>
<td>3386</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>8·09</td>
<td>0·0270</td>
<td>123</td>
<td>3138</td>
<td>5898</td>
<td>2979</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>8·22</td>
<td>0·0488</td>
<td>129</td>
<td>3426</td>
<td>5587</td>
<td>2924</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>8·25</td>
<td>0·0261</td>
<td>142</td>
<td>5175</td>
<td>5223</td>
<td>3042</td>
</tr>
</tbody>
</table>

¹Summer rate was 23 mm d⁻¹, and winter rate was 16 mm d⁻¹.  
²Summer rate was 6 mm d⁻¹, and winter rate was 5 mm d⁻¹.

These rates were much higher than the nutrient uptake of *P. purpureum* reported in Andean Hillsides (Zhiping et al., 2004) and Kenya (Odongo, 2002).

The N, P and K uptake of *P. atratum* and *C. nlemfuensis* was generally lower (*P < 0·05*) compared with *P. purpureum* and *B. mutica* (Table 1). Although *P. atratum* appeared to grow better at the 2·0 ETₚ irrigation rate, qualitative observation showed that it is sensitive to prolonged effluent-saturated soil conditions. This observation contrasts with the observation that *P. atratum* was well adapted to wet, lowland areas in Thailand (Phoatong and Phaikaew, 2001).

**Tissue concentration and uptake of other nutrients**

Adequate levels of other nutrients aside from N, P and K for *P. notatum* forage were as follows: Ca, 5·2 g kg⁻¹; Mg, 3·2 g kg⁻¹; Fe, 100 mg kg⁻¹; Mn, 105 mg kg⁻¹; Zn, 31 mg kg⁻¹; Cu, 11 mg kg⁻¹; and B, 9 mg kg⁻¹ (Mills and Jones, 1996). Based on these levels, tissue concentrations in all the grasses were below adequate for Ca; mostly adequate for Mg and Cu; above adequate for Fe, B and Zn; and deficient to adequate for Mn (Table 1). Sufficient to high levels of micronutrients were observed after the supplementary foliar micronutrient application. Overall, uptake of Fe ranged from 11·0 to 49·0 kg ha⁻¹ year⁻¹; Mn, 2·3 to 4·6 kg ha⁻¹ year⁻¹; Zn, 2·0 to 3·8 kg ha⁻¹ year⁻¹; Cu, 0·4 to 0·7 kg ha⁻¹ year⁻¹; and B, 0·4 to 1·2 kg ha⁻¹ year⁻¹.

The main effects of grass species and irrigation rate as well as their interactions on uptake of other nutrients were significant (*P < 0·05*). Among the grasses, *P. atratum* had the highest (*P < 0·01*) uptake of Mg at 236 and 283 kg ha⁻¹ year⁻¹ for the 2·0 ETₚ and 0·5 ETₚ irrigation rates, respectively, while *P. purpureum* and *P. atratum* receiving 0·5 ETₚ irrigation rate had the highest (*P < 0·01*) Ca uptake of 190 and 192 kg ha⁻¹ year⁻¹, respectively (Table 1). *Paspalium atratum* had an average annual Mg concentration in the dry matter of 6·1 g kg⁻¹ for the 2·0 ETₚ irrigation rate and 7·2 g kg⁻¹ for the 0·5 ETₚ rate, and Ca concentration of 3·9 and 4·9 g kg⁻¹ respectively.

**Nutrient removal as per cent of applied nutrients**

The tropical grasses differed in their ability to remove nutrients (*P < 0·01*) expressed as per cent of effluent applied nutrient (i.e. total annual nutrient uptake in removed biomass divided by cumulative annual nutrient applied). Grasses irrigated at 0·5 ETₚ removed a
higher \((P < 0.01)\) percentage of nutrients (54–94% of N and 44–82% of P) than those irrigated at 2.0 \(\text{ET}_p\) (25–62% of N and 11–23% of P) (Table 3).

\textit{Pennisetum purpureum} consistently removed the highest \((P < 0.05)\) amounts of N (94%) and P (82%) among the grasses irrigated at 0.5 \(\text{ET}_p\) (Table 3). Among the grasses that received the 2.0 \(\text{ET}_p\) rate, \textit{B. mutica} removed the highest percentage of applied nutrient (62% N and 23% P), but these values were not significantly different from the percentage N and P removed by the other grasses \((P > 0.05)\). Removal percentages for K (2–13%), Ca (3–15%) and Mg (1–12%) were rather low, implying a possible accumulation or leaching of these nutrients through the soil. This has important implications on the possible Ca-P precipitation and eventual accumulation of these nutrients in the soil.

\section*{Forage quality}

\subsection*{Crude protein}

High crude protein (\(>150 \text{ g kg}^{-1}\)) forages are desirable for sustained milk yield (22–32 kg milk d\(^{-1}\)) of lactating cattle (NRC, 2001). In this study, the average CP contents of effluent-irrigated grasses were between 90 and 160 g kg\(^{-1}\) during the 2-year period (Figure 5). Averaged across species and irrigation rate, all grasses, except for \textit{P. atratum}, had generally higher average CP content when irrigated at 2.0 \(\text{ET}_p\) rate \((P < 0.01)\).

\subsection*{Neutral detergent fibre}

The energy value of forage is often evaluated using NDF, which is composed of cellulose, hemicellulose and lignin (NRC, 2001). In this study, average forage NDF ranged from 570 to 620 g kg\(^{-1}\) over the 2-year period, with a significant \((P < 0.01)\) main effect of time and an interaction of grass species and irrigation rate. Higher forage NDF was observed during the June–November period when solar radiation and temperature were usually higher (Figure 5).

\subsection*{Acid detergent fibre}

The ADF is composed of the least digestible parts of cell walls such as cellulose, and lignin (NRC, 2001). The ADF of the grasses irrigated with effluent changed with time \((P < 0.01)\) and differed between grass species \((P < 0.01)\) and irrigation rate \((P < 0.01)\). The average ADF of effluent-irrigated grasses ranged from 320 to 360 g kg\(^{-1}\) (Figure 5). As with the NDF, the higher ADF values (up to 400 g kg\(^{-1}\)) were obtained during the period when solar radiation and temperature were higher (June–November) (Figure 5).

\section*{Discussion}

The selected tropical grasses maintained their high productivity when drip-irrigated with dairy effluent at 2.0 \(\text{ET}_p\) rate as evidenced by the higher dry-matter yields and nutrient uptake at this irrigation rate than at the 0.5 \(\text{ET}_p\) rate. The 2.0 \(\text{ET}_p\) rate of application is approximately double the rate typically applied for irrigation to meet the crop water requirement. This high rate of application indicates the high capacity of tropical forage grasses to utilize large amounts of lagoon waste water, if needed.

Effluent-irrigated tropical grasses produced high levels of biomass that were as high or higher than values commonly reported in tropical literature. Among the

\begin{table}[ht]
\centering
\caption{Nutrient removal by various tropical grasses receiving dairy effluent at Waianae, O’ahu, Hawaii, from August 2004 to 2006.}
\begin{tabular}{|l|c|c|c|c|c|c|c|c|c|c|c|}
\hline
\textbf{Irrigation rate} & \textbf{Grass species} & \textbf{N} & \textbf{P} & \textbf{K} & \textbf{Ca} & \textbf{Mg} & \textbf{Fe} & \textbf{Mn} & \textbf{Zn} & \textbf{Cu} & \textbf{B} \\
\hline
2.0 \(\text{ET}_p\) & \textit{Banagrass} (\textit{Pennisetum purpureum}) & 48 & 21 & 5 & 4 & 2 & 35 & 28 & 191 & 3 & 2 \\
 & \textit{California} (\textit{Brachiaria mutica}) & 62 & 23 & 4 & 3 & 2 & 19 & 45 & 206 & 3 & 1 \\
 & \textit{Stargrass} (\textit{Cynodon nlemfuensis}) & 37 & 18 & 2 & 3 & 1 & 26 & 41 & 115 & 2 & 1 \\
 & \textit{Suerte} (\textit{Paspalum atratum}) & 25 & 11 & 2 & 4 & 3 & 81 & 41 & 180 & 2 & 2 \\
0.5 \(\text{ET}_p\) & \textit{Banagrass} (\textit{P. purpureum}) & 94 & 82 & 13 & 15 & 7 & 159 & 83 & 536 & 9 & 6 \\
 & \textit{California} (\textit{B. mutica}) & 72 & 54 & 9 & 8 & 6 & 65 & 86 & 489 & 7 & 3 \\
 & \textit{Stargrass} (\textit{C. nlemfuensis}) & 59 & 65 & 6 & 10 & 4 & 77 & 72 & 359 & 6 & 3 \\
 & \textit{Suerte} (\textit{P. atratum}) & 54 & 44 & 7 & 15 & 12 & 250 & 121 & 694 & 6 & 6 \\
LSD\(_{0.05}\) & & 30 & 11 & 2 & 8 & 4 & 201 & 105 & 383 & 5 & 1 \\
\hline
\end{tabular}
\end{table}

\(^{a}\)Summer rate was 23 mm d\(^{-1}\), and winter rate was 16 mm d\(^{-1}\).

\(^{b}\)Summer rate was 6 mm d\(^{-1}\), and winter rate was 5 mm d\(^{-1}\).

\(\text{ET}_p\), evapotranspiration; LSD, least significant difference.
grasses, B. mutica and P. purpureum produced the highest dry-matter yields and demonstrated the greatest potential to absorb nutrients from the effluent. In support of the observed high forage productivity, the calculated carrying capacity was 8–11 lactating cows ha\(^{-1}\) year\(^{-1}\) using the dry-matter yields of B. mutica and P. purpureum and milk production of 9 kg d\(^{-1}\) of 4% fat-corrected milk (NRC, 2001) for a 607-kg cow (Wilker-son et al., 1997) with dry-matter intake of 21 g kg\(^{-1}\) of body weight (NRC, 2001).

The predicted nutrient uptake from intensively managed, irrigated tropical pasture grasses approached 750–1500 kg N ha\(^{-1}\) year\(^{-1}\) and 75–150 kg P ha\(^{-1}\) year\(^{-1}\) (Russell S. Yost, personal communication). The N and P uptake of effluent-irrigated grasses was mostly within this predicted range of nutrient removal. Despite the deficient P level in forage tissues, P concentrations (2–4 g kg\(^{-1}\)) were all within the typical range of tissue P concentrations (1.5–4.0 g kg\(^{-1}\)) reported for grasses grown in heavily manured soils or certain other high P soils with relatively low P sorption capacities (Mathews et al., 2005). The P content of the forage of effluent-irrigated grass species in this study meets the dietary P requirement of dairy cows according to NRC (2001) guidelines. Farmers feeding their cattle with forage from these species may reduce or eliminate the supplementation of the ration with imported P supplements for sustained milk production.

The recommended Mg concentration in a dairy cattle ration is from 2.5 to 3.5 g kg\(^{-1}\) and slightly higher for early lactating, highly productive cows (4.5 g kg\(^{-1}\)) (Harris et al., 1994), but the Mg level in the forage should not be lower than 2.0 g kg\(^{-1}\) to prevent grass tetany (Voisin, 1963). The high Mg content of P. atratum forage is, therefore, favourable for avoiding the occurrence of grass tetany in dairy cattle. Farmers should be cautioned, however, that very high levels of Mg may favour hypocalcaemia in dairy cows (Chester-Jones et al., 1990), especially if plant Ca levels are low as the case in this study. In contrast, the high levels of K in plant tissues as in the case of P. purpureum reduce the availability of plant Mg in animals (Fisher et al., 1994).

Potassium is very important in dairy cattle diet, being a major mineral component of milk. Generally, cattle require low amounts of K, a minimum of 1–0% or if under heat stress, up to 1–5%, of the total ration dry matter (NRC, 2001). Although the K concentration in the dry matter of P. purpureum was relatively high (Table 1), it can be balanced with other components of the ration to achieve the acceptable K concentration. Some studies have implicated the high level of K in forage to milk fever or parturient paresis, an abnormal physiological event in lactating cattle characterized by rapid reduction in plasma Ca concentrations (Goff and Horst, 1997).

Results also support other researchers’ findings (Clavero, 1997; Wijitphan et al., 2009) that harvesting interval and cutting height affect grass growth and productivity. For example, effluent-irrigated grasses exhibited slower rejuvenation when cut at 27- to 29-d interval. The slow recovery after cutting was probably exacerbated by the low cutting height (8 cm) and the pressure from the relatively heavy weight of the harvesting equipment. This reduction in growth and productivity was greatest on P. purpureum and P. atratum. The growth habit of P. atratum is normally characterized by clump-producing culms. Pennisetum purpureum also has tussocky growth with branching upper culms. With low cutting height, these grasses turned to a prostrate growth habit with higher production of basal tillers. In contrast, B. mutica and C. nlemfuensis have spreading growth habit with rooting runners. Thus, the low cutting height did not adversely affect their growth and productivity.

During the first 3 months of the experiment when cut at 30 cm height, dry-matter yield of P. purpureum, for example, was 9 t ha\(^{-1}\) month\(^{-1}\) (Figure 3). This yield went down to a low 2 t ha\(^{-1}\) month\(^{-1}\) when cutting height was reduced to 8 cm. At low cutting height (8 cm), P. purpureum and P. atratum initially produced more tillers, but after 6 months, these grasses started to exhibit slower growth and less tiller production. The low cutting height may have resulted in the removal of growing points, particularly the apical meristems of the tillers, preventing them from producing new leaves. This may have resulted in reduced carbohydrate production and storage in the stems of tillers and eventually tiller death (Clavero, 1997; Wijitphan et al., 2009). During the second year when harvesting interval was increased (42–44 d), grasses showed the ability to recover better despite the low cutting height.

Deficiencies typical of micronutrients were observed as a general chlorosis of new growth after the fourth month of effluent irrigation. This was likely a consequence of the high soil pH, which resulted in low micronutrient availability (Moraghan and Mascagni, 1991). In addition, dairy effluent supplied only minimal quantities of micronutrients (data not shown). In addition, the relatively high extractable P in the soil may have resulted in antagonistic interactions with Zn (Alloway, 2008). With supplemental micronutrient fertilization, chlorosis had become minimal and increases in the micronutrient levels in the forage were observed. Supplemental applications of micronutrients (Zn, Cu, Fe and Mn) and N were therefore necessary to maintain acceptable tissue levels of these nutrients and prevent chlorosis.

Effluent-irrigated grasses had CP contents that were mostly below 150 g kg\(^{-1}\) possibly due to relatively longer cutting intervals (28–52 d). High forage CP levels...
 (>150 g kg⁻¹) are usually obtained on forages that are well fertilized with N and cut early (17–21 d) (Chin, 1995). In terms of NDF, the values were higher than the recommended minimum values of the forage intended for lactating cows (NRC, 2001), but mostly lower than the range (600–750 g kg⁻¹) reported for many cool-season and tropical grasses (Nelson and Moser, 1994). For example, the NDF of these grasses was lower than that reported by Ruiz et al. (1995) for silages made from *P. purpureum* (680 g kg⁻¹) and *C. dactylon* (745 g kg⁻¹). However, Sarwar et al. (1992) found that increasing NDF from 320 to 480 g kg⁻¹ did not reduce the dry-matter intake and that a minimum of 600 g kg⁻¹ NDF had little effect on milk production.

Both NDF and ADF of the grasses used in this study were generally higher in the June–November period. Warmer temperatures reportedly enhance lignin synthesis resulting in lower digestibility (Buxton and Fales, 1994; Nelson and Moser, 1994). *Paspalum atratum*, *C. nlemfuensis* and *B. mutica* all flower in October–November, which could explain the somewhat higher NDF observed at that time. Forage nutritive value decreases with increasing plant maturity because of increasing structural carbohydrate concentration (ADF, NDF and lignin), with the greatest increase occurring between booting and anthesis (Holman et al., 2007). Based on NDF and ADF values measured from effluent-irrigated grass species, an adjustment in the dietary formulation with allowance for higher proportions from concentrates may be needed when feeding lactating cows with tropical grasses to meet the NRC requirements for NDF and ADF. The recommended minimum dietary NDF values are 250–290 g kg⁻¹ during early lactation and 320–340 g kg⁻¹ during mid- to late lactation (NRC, 2001) to allow cattle to eat more forage. For forage ADF, the recommended minimum is 170–210 g kg⁻¹, but as with NDF, a higher minimum is required for forage ADF depending on various factors that also affect NDF such as particle size, feeding methods, supplements, and rate and extent of fermentability of fibre source, among others (NRC, 2001).

Based on this information, forage quality in this study such as CP, NDF and ADF was at levels that are acceptable for feeding lactating cattle. However, for high-yielding cows, as NDF percentage increases, dry-matter intake generally decreases (Varga et al., 1998). Although a minimum NDF value is needed to keep proper rumen and digestion conditions, generally high values of NDF are not adequate to maintain high milk production levels, especially for high-yielding lactating cows, because of the effect on intake. Because NDF is negatively related to forage digestibility and positively related to fill, daily intake may also be reduced for forages with low NDF values (Varga et al., 1998). As with NDF, higher forage ADF results in reduced digestible dry matter as a consequence of increased lignification of cellulose in the plant (DePeters, 1993). Forage with higher ADF, thus, has lower cellulose digestibility in the rumen, thereby reducing the energy available to the lactating cow for milk production.

In conclusion, *B. mutica* and *P. purpureum* appeared to be excellent choices for forage production to maximize reuse of dairy effluent. Effluent irrigation for forage production appears to be an effective means of recycling energy-expensive nutrients, while reducing the build-up of effluent in lagoons and, in turn, reducing the risk of overflow and contamination of associated water bodies. This recycling partially closes the open nutrient cycle in the dairy production system. With the 2:1 ETp treatments, however, there is a possibility of overwatering and excess nutrient application that could lead to build-up of nutrients in the soil or leaching of nutrient to the environment. This study is preliminary and assessing such impacts is beyond the scope of this manuscript. Further studies with high application rates of animal effluent beyond two years should be conducted to monitor soil nutrient levels and their potential environmental impacts.

**Acknowledgments**

The authors thank the USDA T-Star Program of the University of Hawaii at Manoa, Honolulu, Hawaii, USA, for the project funding and research assistantship support of the lead author. We also thank the CSREES/USDA 406 Water Quality Initiative Competitive Grants Program, Honolulu, Hawaii, USA, for partial funding. We also acknowledge Veronica Wilcox for the initial grass planting and establishment, Zhijun Zhou for the design and establishment of the irrigation system, and colleagues in the laboratory for their invaluable help in soil sample collection and grass harvesting. Reference herein to any specific product, by trade name, trademark, manufacturer or distributor, does not necessarily constitute or imply its endorsement or recommendation by the authors and publishers.

**References**


