Development of Sustainable low cost animal accommodation outwintering pads (OWP's)

Moorepark Research Centre
End of Project report No: 5232

Teagasc

NDP
NATIONAL DEVELOPMENT PLAN

Development of Sustainable low cost animal accommodation outwintering pads (OWP's)

`

Final Report
Project Number 5232

Author

Padraig French and Laura Boyle,
Dairy Production Research Centre, Moorepark, Fermoy, Co. Cork.

Teagasc Headquarters,
Oakpark,
Carlow,
Co. Carlow.

July 2008

Further enquiries to Padraig.french@teagasc.ie

Contents

ANIMAL HEALTH, WELFARE AND PRODUCITIVITY

ENVIRONMENTAL MANAGEMENT

ANIMAL HEALTH, WELFARE AND PRODUCTIVITY

Introduction

Out-wintering pads (OWP) were identified as suitable wintering option for beef cattle as regards animal welfare and production level (Hickey, et al., 2002). They also represent a low cost alternative to cubicle housing for Irish dairy producers looking to increase their herd sizes in order to remain competitive (Donnellen et al., 2002). Kiernan (2004) identified that welfare problems associated with OWP are management and weather dependent and that the potential for high dairy cow welfare standards is good compared to indoor cubicles systems. However this study only investigated dairy heifers and first lactation cows. Further investigation into the appropriate design of these facilities is necessary to determine their potential as a dairy cow accommodation system.

The winter accommodation period has been identified as a time when cows are susceptible to production related diseases, in particular lameness (O'Connell et al., 1997), and also mastitis due to exposure to pathogens. Further to this, in seasonal spring calving systems winter accommodation coincides with the transition period around calving. This period is critical in terms of health as the cow is under severe stress due to the physical process of parturition, changes in hormone levels, and the physiological changes involved in initiation of lactation. Therefore it is important that cows are managed under conditions that do not compromise health during this period. The most common form of accommodation in Ireland for dairy cows during the winter is cubicle housing with concrete flooring (Egan et al., 2001). However, this type of accommodation has been identified as presenting challenges to the cow. Concrete flooring is recognised as a factor in the development of hoof lesions and lameness (Webster, 2001). Lameness is one of the most serious threats to dairy cow welfare due to its associated pain and widespread occurrence (Clarkson, et al., 1996). OWPs have a soft, yielding substrate to stand on with little risk of slipping, which may be beneficial for hoof health. However, the hooves are more likely to be exposed to dirty, unhygienic conditions on OWP and this could lead to heel erosion (Hickey, et al., 2002). Therefore some form of manure removal system, particularly from the feed area, may be important. This may also have implications for the susceptibility of animals to mastitis both during the accommodation period and during the subsequent lactation, as dirty conditions are associated with poor udder health and increase in mastitis (Barrett, 1992). Fisher et al. (2003) showed that cows are reluctant to lie down on wet, muddy surfaces and this could be a problem with an unsheltered OWP. Also, behavioural synchrony is recognised in several species (Conner et. al., 2006) and is an important indicator of dairy cow welfare (Miller and Wood-Gush, 1991). The term is used both to describe behaviours that are non-randomly distributed in a temporal manner (Hastie et al., 2003) and behaviours that occur amongst all members of a group at once (Connor et al., 2006). A lack of behavioural synchrony may be indicative that the accommodation system may not satisfy the normal behavioural requirements of the animals. Beef cattle on OWPs perform better than animals indoors on slats (Hickey et al., 2002) and yearling dairy heifers on OWP use their feed more efficiently than animals indoors (Boyle, 2004). However, out-wintered animals have higher energy demands during periods of adverse weather. Given the susceptibility of dairy cows to negative energy balance problems in early lactation, out-wintering on OWP may have negative implications for productivity and reproductive performance during lactation.

The aims of this study were to compare three different OWP designs with cubicle housing in terms of hoof and udder health, dirtiness scores, animal behaviour and productivity. The study was conducted over the winters 2004/2005 and 2005/2006. The pad designs investigated were: Sheltered and unsheltered pads where cows were fed from a concrete apron adjacent to the woodchip lying area and an unsheltered self-feed pad where cows self-fed from a silage pit on top of the woodchip lying area. The latter design option was not included in the first year of the study. In that year the space allowance also differed between the sheltered and unsheltered pads. In the second year of the study animals in all three pad designs had the same space allowance.

Experiment 1

Year 1

One hundred and forty seven pregnant dairy cows (*Bos Taurus*) (44 primiparous and 103 multiparous) were blocked according to breed [Holstein-Fresian (HF), Normande (NM), Montbeliarde (MB), Norwegian Red (NRF), Montbeliarde x Holstein-Friesian (MBX), Normande x Holstein-Friesian (NMX)], parity (1.78 ± 1.58), expected calving date (ECD) (mean ECD: 21 Feb 2005 ± 25.5 days) and body condition score (BCS) (3.09 ± 0.29). Cows were then randomly assigned to one of three treatments from the 6th December 2004; (i) indoor cubicle housing; (ii) an unsheltered OWP and (iii) a sheltered OWP. Indoors the cubicles were bedded with rubber mats and were provided at a ratio of 1:1. They were of a 'Super Dutch Comfort' design (O'Connell, et al., 1991) and were manually cleaned and treated with lime each day. An automatic scraper cleaned the solid concrete floor 6 times daily. Cows self fed silage from a concrete feed face with 40cm space per cow. The design and layout of the two OWPs used in the experiment is provided in Figure 1. The woodchipped lying areas were constructed according to published guidelines (see Hickey et al., 2002 for details). Cows on the unsheltered pad had a woodchipped space allowance of 12m^2 per head while cows on the sheltered pad were provided with 6m^2 woodchipped surface. The latter OWP was sheltered on two sides by erecting a 1.83m high semi-porous barrier (Nicofence®, R.J.M. Mooney & Son Ltd., Dublin 12, Ireland.), and overhead by a green polythene tunnel.

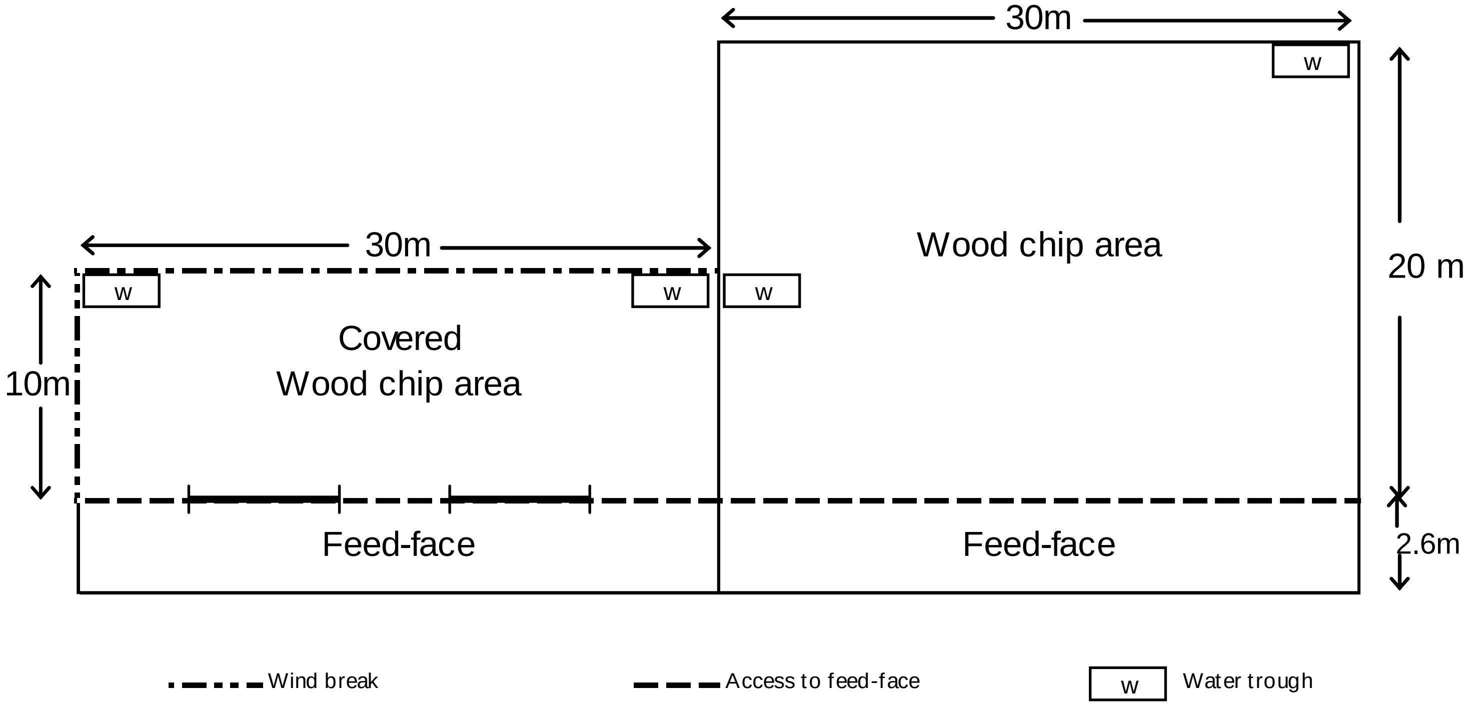

Figure 1. ***Design and layout of the two out-wintering pads used in the experiment***

Year 2

Cows (n=96) were assigned to four treatments , each replicated twice, using a randomised complete block design from 17 Nov 2005 (pluriparous) or 5 Dec 2005 (primiparous) until calving (mean=21 Feb 2006) when they were turned out to pasture. Treatments were (i) indoor cubicle housing (same as for year 1); (ii) an unsheltered OWP (Figure 1); (iii) a sheltered OWP (Figure 1) and (iv) a self-feed pad that had a silage pit constructed directly on the woodchip. Cows on the sheltered and unsheltered pads with the feed apron had a space allowance on the woodchips of 12m^2 and on the concrete of 2.52 m^2. The concrete was cleaned 6 times per day. Self-feed cows had a woodchip space allowance of 14.52m^2. All OWPs were managed so that each cow had a minimum clean lying area of 2.2 m^2.

Measurements

Foot health and locomotion

The hind feet of each animal were examined and correctively pared prior to the start of each experiment. Scoring was carried out by the same person throughout the trial in order to eliminate an observer effect. The hind claws were cleaned and a sliver of horn was pared from the whole area of the weight-bearing surface to expose fresh horn. Soles that were pigmented were recorded, as dark pigmentation affects identification of bruises. Sole haemorrhages were localised as to zone of the sole (6 regions as per Greenough and Vermunt, 1990), and their severity scored on a subjective 5-point scale (1 = diffuse red, 2 = stronger red colouration, 3 = deep dense red, 4 = port coloration and 5 = red raw, possibly fresh blood, from Leach et al., 1998**.** Sole ulcers were scored from 6 to 8 (6 = corium exposed, 7 = severe sole ulcer – major loss of horn, and 8 = infected sole ulcer, (Leach, et al., 1998). Both sole haemorrhage and sole ulcer scores were geometrically adjusted in order to produce a severity score (sole haemorrhage: 1, 2, 4, 8 and 16, sole ulcer: 32, 64 and 128). This method of scoring recognises the greater clinical significance of higher scores (Greenough and Vermunt, 1991). The scores for all four claws were added to give a total sole lesion score for each animal at each inspection. Presence of heel horn erosion (HE) was also determined according to a scale described by Peterse (1980). Heel bulbs on both claws were examined, and rated on a four-point scale (0 = no symptoms, 1 = slight pock marking and/or superficial horn defects in the axial surface of the bulb, 2 = some large fissures in the horn of the bulb but not extending to the corium, 3 = disappearance of the heel horn and/or deep defects in the horn of the bulb extending to the corium). White line disease (WLD) and the presence of under-run sole were recorded as present or absent. During both years of the study lesions were scored at housing and calving. During year 1 they were also scored 6 & 12 weeks post partum (pp) and year 2 at 9 & 14 weeks pp. In addition in year 2, hardness (Shore D scale) of all 4 claws was recorded at each inspection using an analogue duromoter.

Locomotion score was determined using a subjective scoring system modified from O'Callaghan et al. (2003). In year 1 cows were scored at assignment to treatment, and thereafter on a fortnightly basis prior to calving until there were a minimum of 18 animals in each treatment that had not calved (6 examinations in total). Animals were scored post calving on a weekly basis for 13 weeks. In year 2 cows were scored on a weekly basis after calving for 14 weeks.

Animal behaviour

In year 1 twelve cows in each treatment were selected as focal animals for behavioural observations. They were selected by block, on the basis of mean expected calving date per block and remained with the rest of the group, but were marked with tail paint in order to facilitate identification. Three people carried out the observations, and they alternated daily between the treatments in order to reduce the observer effect. Behaviour was recorded on a hand held computer (Psion Walkabout) using The Observer Event Recorder (Noldus Information Technology, Wageningen, The Netherlands) by scan sampling (Martin and Bateson, 1993). Observations were carried out for 8 hours per day (between 08:00 - 12:00 and 13:00 –17:00), 2 days per week during weeks 8, 9, 10 and 11. Behaviour (eat, ruminate, active, idle, sleep), posture (stand, lie) and location (indoors: cubicle i.e. lying area, passageway, feed-face; OWP: woodchip area i.e. lying area, feed face) of the cows were recorded every 15 minutes (Mitlohner, et al., 2001).

In year 2 the group was considered the experimental unit, as there were replicates for all treatments. This year the outcomes for measurement were eligible cows lying (ECL = number of cows lying divided by the number of cows not eating), cow comfort index (CCI = the number of cows lying divided by the number of cows touching the lying ares) and proportion animals feeding (AF).

Behavioural observations were carried between 06:00 and 01:30 on three occasions (6-10 Jan, 9-11 Feb and 26-28 Feb) by two observers using scan sampling. The number of animals standing, lying and feeding was recorded every 30min, as well as the location i.e. bed area (cubicle or woodchip), feedface, or passageway. The CCI, ECL and AF values were calculated from these data for each treatment at each time point.

Animal behaviour was also recorded using automatic grazing recorders (IGER) and dataloggers that record standing and lying behaviour. Animals (n=12 from each treatment) were fitted with the equipment twice: for 24 hours while at pasture, prior to entering winter accommodation and still lactating, and for 24 hours when accommodated in their treatment groups, and dried off.

Udder health, animal and pad cleanliness

In the first year of the study cows were scored for dirtiness prior to housing, then fortnightly (14 ± 0.6 days) until calving. Cows were quarter milk sampled (QMS) for microbiology and somatic cell count (SCC) prior to housing, at drying off and approx. 3 weeks post partum. QMS were also collected 2.2 ± 1.98 days post calving and assayed for California Mastitis Test (CMT) and microbiology. Clinical mastitis (CM) was diagnosed when macroscopic changes in the milk or udder were observed. Sub-clinical mastitis (SCM) was diagnosed in the event of SCC > 200,000, CMT > 1, without macroscopic changes. SCC was recorded at 2 week intervals throughout the following lactation. A log2 transformation of SCC to SCS was used to normalize the data distribution.

In year 2 cows were scored for dirtiness at the beginning of the experiment, then at approx 3 week intervals (17±3.3 days) until 30 January. Only animals that had not yet calved were scored. Cows were quarter milk sampled (QMS) for microbiology and SCC, at drying off (30 November 2005), approx. 3 weeks (18.3±3.52 days) post partum, and on 14 June 2006. QMS were also collected 1.8 ± 1.29 days post calving and assayed for CMT and microbiology. CM was diagnosed at each QMS test day when macroscopic changes in the milk or udder were observed. Incidence of CM was also recorded during the winter housing period and the following lactation. SCM was diagnosed at each QMS examination in the event of SCC > 200,000, CMT > 1, without macroscopic changes. SCC was recorded at 2 week intervals throughout the lactation. A log2 transformation of SCC to SCS was used to normalize the data distribution.

In addition, the OWPs were scored weekly using a visual dirt scale (DS) (1-4; 1=clean, 4=dirty) and composite woodchip samples were taken from the OWP surface. Samples were analysed for dry matter (DM) and pH. Presence of bacteria (staphlococci, streptococci, and coliforms) and bacterial load (no. colonies per agar plate) from each sample were determined using selective media. Bacterial loads were classified as low = <40 colonies, medium = >40, <200 colonies, high = >200 colonies.

Performance

In year 1 liveweights were collected weekly from assignment to accommodation until the end of the subsequent lactation. Body condition score (BCS) was recorded at approximately monthly intervals from the start of the experiment. BCS was recorded by the same person on a scale of 1 to 5 as described by Wildman et al. (1982). Milk yield was recorded weekly for the entire lactation. Yields were recorded using electronic milk meters (Dairymaster, Causeway, co. Kerry, Ireland). In addition, milk composition (concentrations of fat, protein and lactose) was determined in one successive morning and evening sample of milk per week using a Milkoscan 203 instrument (Foss Electric DK-3400 Hillerod, Denmark). Average milk yield for three stages of lactation (1 =-60 days in milk; 2 = 61– 220 days in milk; 3 = 221 days in milk to the end of the lacation).

Climatic energy demand (CED) calculations were estimated for 10 animals in each treatment, based on the model of Higgins and Dodd (1989) and adapted from Hickey et al. (2002). It was calculated on three consecutive days each week between 20 December and 16 January. CED calculations were carried out using meteorological data that was collected on site using an automatic weather station and temperature and relative humidity dataloggers placed in each treatment. For the purpose of the CED model wind speed in Tunnel and Indoors was assumed to be 1.5m/sec, and rainfall was considered to be 0. Heat energy production (HE) was calculated once per week between 20 December and 16 January for the 10 animals from each treatment that underwent CED estimation.

In year 2 of the study, liveweights were recorded weekly, and BCS at approximately 6 week intervals (6.8±3.82 weeks), from the start of the winter accommodation period until the end of the following lactation. Feed intakes were estimated using the N-alkane technique between 22 and 27 January 2006. Weekly milk yield and composition were recorded from calving until the end of the lactation. Average weekly milk yield was calculated for three stages of lactation: 6 to 60 days in milk (DIM) (stage 1), 61 to 220 DIM (stage 2), and 221 to 305 DIM (stage 3). Gestation duration, calving to 1st service interval, 21day submission rate, 1st service pregnancy rate and calving to conception interval (CCI) were also calculated.

Animal reproductive performance was evaluated on each treatment by calculating the number of services per cow, percentage in calf, pregnancy to 1st service submission rate and the 6 week in calf number.

RESULTS

Foot health and lameness

In year 1 only one animal developed a sole ulcer during the experiment, and this was an IC cow at the 12 week examination. All other sole lesions consisted of sole haemorrhages. There was no overall effect of treatment on sole lesion scores (P>0.05). However, there was an effect of inspection date and an interaction between treatment and inspection date (both P<0.001; Figure 2). Sole lesion score at calving (8.60 ± 0.717) was higher than at 6 weeks post calving (5.26 ± 0.694; P<0.001). However, sole lesion score 12 weeks post calving (15.03 ± 1.115) was higher than at either of the other two examinations (both P<0.001). Figure 2 shows how the pattern of lesion severity in each treatment varied over time.

Sole lesion scores of IC cows were lower 6 weeks post calving than either at calving (P<0.01) or at 12 weeks post calving (P<0.05), but there was no difference between score at calving and at 12 weeks. At 12 weeks post-partum lesion scores in CP cows were higher than at 6 weeks post-partum (P < 0.001) and tended to be higher than that at calving (P=0.06). There was no difference between score at calving and 6 weeks post calving (P>0.05). Similarly, there was no difference in sole lesion scores of UP cows at calving and the 6 week post-partum inspections (P>0.05). However scores at 12 weeks post calving were significantly higher than at calving (P<0.001), and 6 weeks post-calving (P<0.001). Furthermore, at the 12 week post calving examination sole lesion scores in UP were higher than those in IC (P<0.05). There was no treatment effect or interaction between treatment and examination on HE score (P>0.05, data not shown). However, there was an effect of time (P<0.001). Score at calving (4.5 ± 0.25) was higher than that at 6 weeks (3.0 ± 0.17; P<0.001) and at 12 weeks (2.7 ± 0.18; P<0.001). However, there was no difference between the latter two examinations.

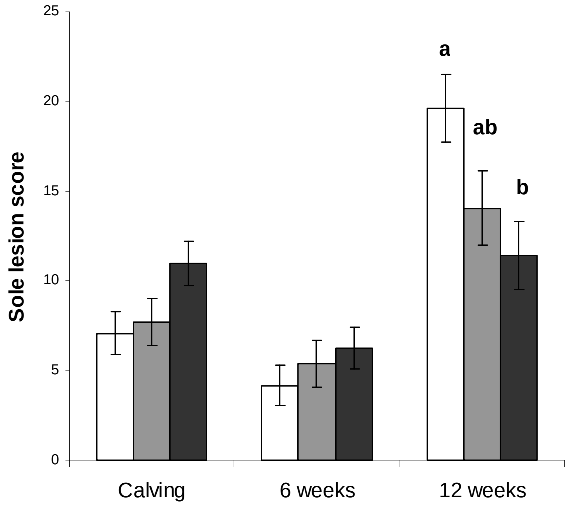

Figure 2 Mean (least squares) sole lesion scores at housing, calving, 6 and 12 weeks post -partum (Unsheltered OWP = □, Sheltered OWP = ▒, Indoor cubicles = ■)

In year 2 treatment had no effect on sole lesion scores, but scores increased over time ($P<0.001$). Self-feed cows had higher heel erosion scores than cows in cubicles or on the sheltered pad ($P<0.01$). They also had higher dermatitis scores than cows indoors in cubicles ($P<0.01$) and cows on the sheltered pad ($P<0.05$) at calving, and tended to have higher scores than cubicle cows 8 weeks post calving ($P=0.06$). Lateral claws were harder than medial claws ($P<0.001$). Hoof hardness was highest at housing and decreased thereafter up to 8 weeks pp ($P<0.05$). The hooves of cows in cubicles and on the sheltered pad were harder than those of cows on the self-feed and unsheltered pads ($P<0.05$).

Animal behaviour

In year 1 of the study cows on the unsheltered pad spent significantly more time standing in the lying area ($P<0.001$), idling ($P<0.01$) and idling while standing ($P<0.001$) than animals in the sheltered pad or indoors in cubicles (Table 1). Cows indoors in cubicles spent the lowest amount of time feeding and more time ruminating than animals on the OWPs ($P<0.01$). Furthermore, cows indoors in cubicles spent the lowest proportion of their standing time in the cubicles ($P<0.05$).

Behaviour	Sheltered pad	Cubicles	Unsheltered pad	s.e.m.	Treatment
Standing less eating	0.3720	0.4106	0.4199	0.0080	NS
Standing in lying area	0.1658^{a}	0.1111^{b}	0.2903^{c}	0.0087	0.001
Total idle (standing + lying)	0.1670^{a}	0.1847^{a}	0.2160^{b}	0.0051	0.01
Standing idle	0.1038^{a}	0.1104^{a}	0.1602^{b}	0.0061	0.001
Feeding	0.4059^{a}	0.3304^{b}	0.3673^{ab}	0.0081	0.01
Total rumination (standing + lying)	0.3088^{a}	0.3450^{b}	0.2839^{a}	0.0066	0.01

Table 1. **Proportion time spent performing each behaviour during daylight hours. Superscripts indicate significant differences.**

In year 2 autocorrelation of eligible cows lying (ECL), cow comfort index (CCI) and proportion animals feeding (AF) varied between treatments. Indoor cubicles had the lowest (39.6%) and the self-feed pad the highest (73.3%) autocorrelation of ECL ($P<0.01$). All OWP designs had higher autocorrelation of CCI than cubicles ($P<0.001$). There was also an effect of treatment on autocorrelation of AF ($P<0.05$), being lowest in cubicles (32.8%), and highest in the sheltered pad (54.9%). Treatment also had an effect on the mean daily proportion of ECL, CCI and AF ($P<0.001$). The highest mean proportion of ECL occurred indoors (60%), and lowest in self-feed (44%). As seen in Figure 3, highest values for ECL in the OWPs were in the early morning (>90%), and in the late evening. Low ECL values (<1%) were recorded in all OWPs at 17:30 and 18:00.

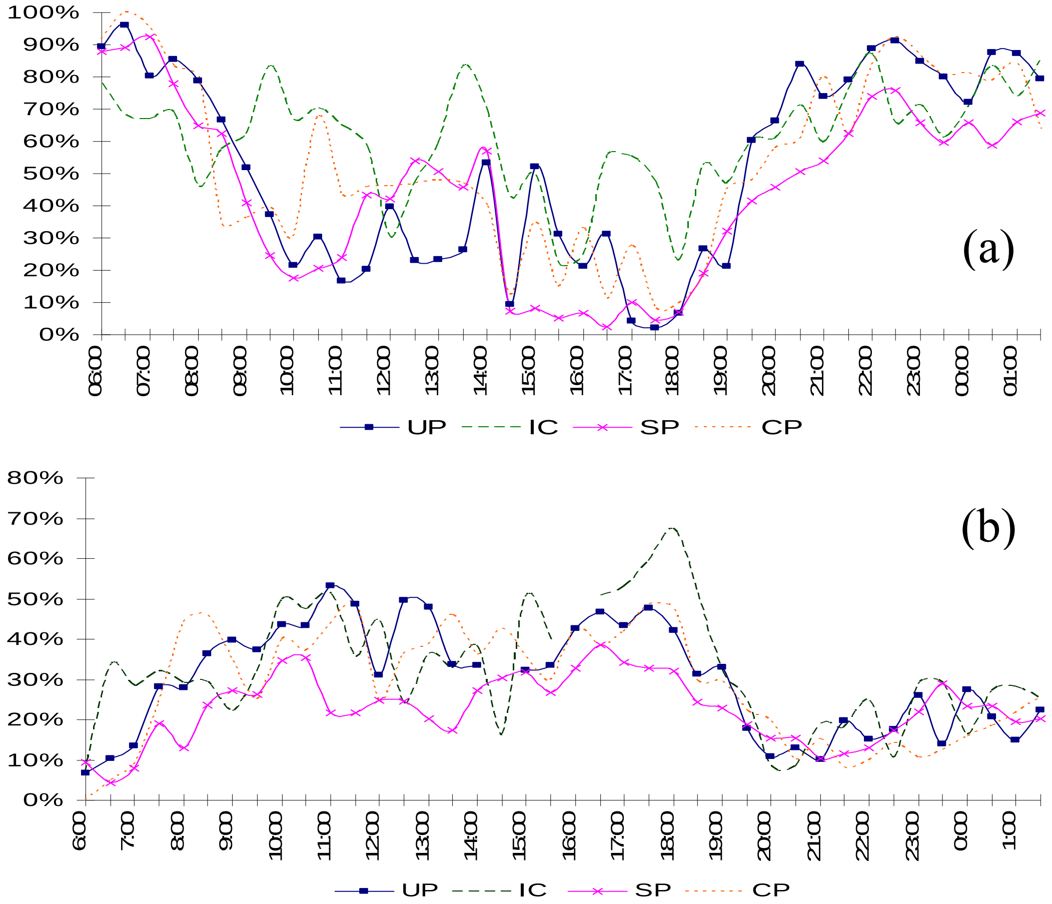

Figure 3 a) mean proportion ECL in each treatment at each observation period. **b)** mean proportion AF at each observation period.

With regard to animal behaviour recorded during the autumn while lactating and in the winter accommodations, cows spent more time feeding at pasture (536.6±12.7 and 466.6±12.9 min respectively; $P<0.001$) due to longer feeding bouts (51.8 and 39.7; $P<0.001$). However, the number of feeding bouts was higher in the winter accommodation (8.1±0.39 and 10.9±0.39; $P<0.001$). Reduction in duration and increase in number of feeding bouts were greatest in UP ($P<0.01$) and SF ($P=0.06$). In the winter accommodation cows had fewer bites/min than at pasture (29.3±1.12 and 57.2±0.74; $P<0.001$). They also lay longer during the winter than at pasture (no. lying datapoints=135.2±3.54 and 115.3±3.16; $P<0.001$). In the OWPs this was due to longer lying bouts ($P<0.05$) but in the cubicle house it was due to an increased number of bouts ($P<0.001$).

Udder health, animal and pad cleanliness

In year 1 cows on the sheltered pad were dirtiest with cows in cubicles the cleanest and cows outdoors on the unsheltered pad intermediary ($P<0.05$).). Four cases of CM (as diagnosed by the stockperson) were recorded in IC, 2 cases in CP and 2 in UP during the winter accommodation period. Post calving three cases were recorded in IC, nine in CP and seven in UP. However, treatment did not affect the proportion of animals that developed clinical mastitis ($P>0.05$, data not shown).

There was no difference in the proportion of animals from each treatment diagnosed with subclinical mastitis at any of the quarter sampling test dates ($P>0.05$, data not shown). However there was an effect of test day ($P<0.001$). The proportion animals that had at least one quarter affected with subclinical mastitis at drying off, calving and the three weeks post calving test was 84%, 55% and 46%

respectively. The odds of an animal having at least one affected quarter was lower at calving than at drying off (OR=0.25, CI=0.12-0.52, P<0.001), and at three weeks post calving than at drying off (OR=0.17, CI=0.09-0.35, P<0.001).

Treatment tended to have an effect on the proportion animals that had an IMI (P=0.08), with a higher proportion in CP than UP (OR=2.0, CI=0.99 – 4.04; P=0.05). There also tended to be fewer cows in UP that had an IMI than in IC (OR=0.5, CI=0.23 - 1.04; P=0.06). There was an effect of test day (P<0.05), with a higher proportion of animals having an IMI isolated three weeks post calving than at drying off (OR=1.95, CI=1.10 – 3.49; P<0.05)

In year 2 self-feed cows had the highest dirtiness scores (9.8±0.27, mean±s.e.) and cows in the sheltered pad the lowest (8.3±0.27; P<0.001). However, there was no difference in animal dirtiness score between treatments at the final exam which was just after the pads had been cleaned off. Dirtiness scores in cubicles remained at a similar level throughout the course of the experiment (P>0.05). Animals in the sheltered pad had numerically the lowest score at the initial exam, and a score similar to cubicle cows on all other occasions. However, dirtiness scores in the unsheltered and self-feed pads increased from the start of the accommodation period until the OWPs were cleaned.

In year 2 there was only 1 case of CM during the dry period, and this occurred in the self-feed treatment. There was no difference in the proportion of animals in each treatment diagnosed with SCM at drying-off, at calving, three weeks post calving, or on 14 June 2006 (P>0.05, data not shown). However, there was an effect of time. The herd percentage of animals having at least one quarter affected at drying off, calving, three weeks post calving and on 14 June was 64%, 57%, 32% and 25% respectively. There was no difference between drying off and calving, but at both of the subsequent examinations there were fewer animals with subclinical mastitis than at drying off (P<0.001). There was no effect of treatment or inspection on the proportion of animals that had IMI (P>0.05 in all cases, data not shown).

There was no interactive effect of treatment and lactation week on SCS during either year (P>0.05). During year 1 there was an effect of treatment on SCS (P<0.05). Cows on CP had higher SCSs (16.2±0.13) than IC (15.7±0.13; P<0.05). However, there was no difference between UP (16.0±0.13) and either other treatments. During year 2 there was no difference in SCS between any of the treatments (15.5 ± 0.22, 15.0 ± 0.24, 14.9 ± 0.24, 15.6 ± 0.23; IC, UP, SP, CP respectively).

The unsheltered and self-feed pads had higher dirt scores than the sheltered pad (P<0.01). Dirt scores increased with weeks in use (P<0.001). Woodchip dry matter was lower in the unsheltered and self-feed pads than in the sheltered pad (P<0.01), and dry mater decreased with weeks in use (P<0.001). There was no effect of treatment on pH, and although the effect of time was significant (P<0.05) there was no discernable pattern over time. There was no difference between treatment samples in either presence or load of Staphylococci sp or in the number of samples per treatment that contained Streptococci spp, but the self-feed pad had more samples with a high load (P<0.01). More samples from the self-feed pad contained Coliform spp (P<0.05), due to a higher number of samples with a low and medium bacterial load.

Performance

During both years average daily weight gain did not differ significantly between treatments either before calving, or during the lactation. In year 1 there was a significant effect of treatment (P<0.01) and of treatment over time (P<0.001) on pre-calving body condition score (BCS). Overall, the BCS of animals housed indoors was higher than UP animals (P<0.001) and had a tendency to be higher than animals in CP (P=0.07). Approximately two months after assignment to treatment a significant difference between BCS in UP and IC became apparent (P<0.05). After three months on treatment this difference had increased (P<0.01), and there was also a significant difference between BCS in CP and

IC ($P < 0.01$). There was no effect of treatment on daily milk yield or composition. There were no treatment differences in any of the reproductive parameters in year 1.

In year 2 winter accommodation had no effect on liveweight or BCS prior to calving or during lactation ($P>0.05$, data not shown). However, cows on SP tended to produce milk with a higher protein percentage than CP animals (Table 2). They also had the highest mean weekly milk yield over the entire lactation and during stage 1. Furthermore, the self-feed cows had the highest 21d submission rate, 1st service pregnancy rate, and numerically the lowest calving to 1st service interval and CCI.

Table 2. Production and reproductive data from year 2

	Cubicles	Sheltered pad	Unsheltered pad	Self-feed	P
Overall weekly milk yield (kg)	122.1^{c}	123.6	131.9	136.9^{d}	0.05
Stage 1 weekly yield (kg)	162.5	158.7^{c}	177.7	178.2^{d}	0.05
Stage 2 weekly yield (kg)	134.0	134.3	135.5	146.6	NS
Stage 3 weekly yield (kg)	133.5	133.6	136.1	146.5	NS
Protein %	3.48	3.46	3.42^{a}	3.52^{b}	0.1
Fat %	3.92	3.95	3.86	3.94	NS
Lactose %	4.52	4.49	4.46	4.45	NS
DMI (kg/day)	10.6	10.5	11.3	10.0	NS
Calving to 1st service (days)	76	75	80	70	NS
21d submission rate (%)	70	67	68	85	-
1st service pregnancy rate (%)	30	33	32	55	-
CCI (days)	101	93	94	93	NS
Gestation duration (days)	282	286	284	280	NS

ns =non-significant, $^{a, b, c,d}$ values within lines indicate differences between differing letters, $P< 0.1$, $P<0.05$ respectively

Treatment had a significant effect on CED ($P < 0.001$). Demand on UP was significantly higher than CP and IC (6.05, 5.59 and 5.58 Mj/m^2 respectively, $P < 0.001$, s.e.m. = 0.02). The difference in heat production between treatments was also significant ($P < 0.05$), being significantly lower in UP than IC (11.36, 13.72 and 13.05 Mj/m^2, $P < 0.05$, s.e.m. = 0.19). There was also an effect of date, and an interaction between treatment and date ($P < 0.001$) for both CED and heat production. Heat production never fell below CED for any animal over the days that weather recordings were made.

DISCUSSION

Foot health

In year 1 of the experiment cows housed indoors in cubicles had higher sole bruise scores at calving than cows on either OWP design. This may have arisen due to prolonged time spent standing on concrete in late pregnancy as this is a known pre-disposing cause of sole haemorrhages at calving (Webster, 2001). The cubicle housed cows did not spend any longer standing in total than the animals on both OWP designs. However, they did spend very little of their standing time in the lying area which in their case was the cubicles. The mat bedded cubicles would have given the cows relief for their feet from the concrete while standing (Leonard et al., 1996). Cows on both OWP designs had better foot health at calving, probably because the cushioning properties of the woodchips protected their feet from injury in late pregnancy. Nevertheless sole bruise scores increased rapidly once they were turned out to grass. This was particularly true for the cows housed on the unsheltered pad. These animals spent the highest amount of time standing in the lying area i.e. on the wood-chips. It is likely that constant exposure to the wet and muddy conditions on the pad softened the hooves (Borderas et al., 2004). This pre-disposed them to bruises once the cows were turned out to grass and had to walk on the farm roadways twice daily. This was confirmed by the findings from year 2 which showed that animals in cubicles and the sheltered pad had harder hooves than cows on both unsheltered designs. Nevertheless, sole bruise scores did not differ between treatments in year 2 of the experiment. However, in accordance with Hickey et al. (2002) cows on the self-feed pad had higher scores for conditions more often associated with dirty, unhygienic conditions indoors i.e. heel erosion and dermatitis. The post and rail concrete feed face associated with the sheltered and unsheltered pad designs meant that most of the excreta produced by the cows was removed from the feeding area. The hooves of cows that self-fed on the woodchips were constantly exposed to excreta which resulted in problems with heel erosion and dermatitis, an infectious condition of the skin of the hooves. In light of these findings the optimum pad design features for foot health involve shelter and a concrete apron that is regularly cleaned for the cows to feed from.

Behaviour

High standing and idling times by cows on the unsheltered pad in year 1 of the study indicated that the woodchips were too dirty and wet for the cows to use them for lying. Obviously this problem could be addressed to a large extent simply by more frequent cleaning of the pad. The findings from year 2 indicate that the OWPs are associated with important benefits to animal behaviour. High autocorrelation values associated with the three OWP designs investigated in year 2 indicated that there was much stronger behavioural synchronisation, which is a positive welfare indicator, on the pads then indoors. It is likely that the soft underfoot surface and lack of physical barriers on the OWPs enabled greater freedom of movement compared to indoors and this improved the ability of the animals to synchronise their behaviour. Furthermore, cows on OWP probably have less difficulty maintaining visual contact with conspecifics than do cows indoors in cubicles.

The behavioural results from year 2 of the study also indicate that there was more resting at night, which is the normal resting time for dairy cows, on the OWP compared to the cubicles. This is in accordance with Hassoun (2002) who found that cows at pasture spend more time resting at night than during the day. This indicates that animals on an OWP have a more ‘natural’ circadian rhythm.

Susceptibility to environmental stressors may have caused unsheltered cows to modify feeding behaviour more than sheltered cows once they moved into their winter accommodation. Shorter eating times and fewer bites/min during the winter are likely due to reduced nutritional need as cows were no longer lactating. This could have facilitated increased lying time during WIN. Long lying bouts are indicative of comfort while lying, thereby implying OWPs provide a highly acceptable lying surface.

Udder health, animal and pad cleanliness

In the first year of the study cows on the sheltered pad were much dirtier than in the other treatments. Furthermore, animals in this treatment had reduced udder health, and higher somatic cell scores. This was largely due to the high stocking density employed in this treatment. With the inclusion of the self-feed OWP in year 2 and a reduction in the stocking density of the sheltered OWP a completely different set of results were obtained. Cows in the OWP with the self feed silage pit had the highest dirtiness scores and cows on the sheltered pad the lowest, although there was no difference in animal dirtiness score between treatments at the final exam just after the pads had been cleaned off. These results indicate that animal cleanliness is largely determined by the frequency of pad cleaning. The results also suggest that unsheltered and self-feed pads probably need more frequent cleaning than sheltered pads given that these OWP were consistently dirtier during year 2 of the experiment. More worryingly the self-feed pad had more samples with a high load of Staphylococci sp and more samples contained Coliform spp due to a higher number of samples with a low and medium bacterial load. Furthermore, although there was only one case of clinical mastitis during the dry period this occurred in the self-feed treatment. In contrast to design options where cows are fed off concrete, all the excreta from cows that self-feed silage on the OWP is deposited on the woodchips resulting in higher bacterial loads in this system.

Nevertheless there was no effect of housing treatment in the second year of the study on cow udder health or mastitis incidence. This indicates that in spite of potentially dirtier conditions on OWP compared to cubicles, OWPs can be managed so that milk quality and udder health are not compromised.

Production

In year 1 cows indoors in cubicles spent the lowest amount of time feeding and more time ruminating than animals on OWPs. Furthermore, CED was lower indoors than outdoors. These results may explain the higher BCS scores in these animals, and probably reflects the lower energy requirements of housed animals.

However in year 2 differences in reproductive performance and milk production between the housing systems appear to have been driven more by feeding system than accommodation type *per se.* Cows on the self-feed pad that had continuous access to food performed better in these areas than animals that had access to post and rail feeding systems in the other three treatments. It appears that OWP designs that facilitate the self-feeding of cows have the potential to improve productivity and reproductive performance probably mediated by higher feed intakes in such systems. Findings from both years however highlight that the absence of shelter for cows on OWP during the winter period does not have a negative impact on measures of performance during lactation.

CONCLUSIONS

It is clear that there is better potential for high cow welfare standards on OWP than indoors in cubicles. OWP facilitate more natural behaviour patterns as well as providing a soft substrate that may improve locomotion during the following lactation. Potential welfare problems for animals on OWP include prolonged standing leading to heightened susceptibility of the hooves to bruising during lactation as well as clinical mastitis and infectious hoof conditions. These problems are largely dependent on pad cleanliness and to a lesser extent on the provision of shelter and stocking density. The improved performance results with the self-feed option make it an attractive option; however, keeping the woodchips clean in such a system could prove challenging.

ENVIRONMENTAL MANAGEMENT

Introduction

Use of OWPs generates spent timber residue (timber and manure) and effluent (rain water and urine) that must be disposed of after each winter. Nutrients are retained in the spent timber residue (STR) and effluent and can be recycled within the farm system. Nitrogen (N) loss from agricultural systems is a significant source of nutrient pollution to waterways and the atmosphere. Therefore, OWPs require evaluation in terms of N recycling within the farm system to ensure N loss is minimized. This project employed field experiments and modelling to determine whether land application of OWP materials (STR and effluent) is an appropriate waste management strategy for out-wintering pad systems.

Nutrient analysis of STR and effluent indicated the materials had sufficient N content to be potential fertiliser sources for grassland. Field experiments provided an approximation of the N contribution of waste materials from OWPs to grassland fertilization. The data showed from 12 to 26% of timber residue was incorporated into soil on Irish grassland over one growing season. Nitrogen in STR was not taken up by herbage within a four month growing period. Nitrogen in effluent was an effective fertiliser source for grassland and was utilized as efficiently as inorganic N fertiliser for silage yield within the first six weeks of growth.

Management of livestock waste from OWPs was analyzed in terms of the EU Nitrates Directive on N fertiliser use to assist in determining the overall sustainability of land application of spent materials. Integration of results from field experiments on STR and effluent indicated that land application of OWP materials required greater inorganic N fertiliser inputs or resulted in lower silage yield compared to land application of slurry from conventional livestock housing. Land application of OWP materials failed to improve N recycling compared to the conventional system. The research demonstrated that alternative waste management strategies for OWPs must be developed which maximize N recycling and thus minimize the extent of N loss from OWPs to the environment.

The objective of this research was to determine whether OWPs are an effective solution to expanding livestock production with respect to N recycling from land application of spent OWP materials. Ultimately, this research provided the scientific basis to underpin guidelines for the development of waste management strategies to optimize N recycling and sustainability of OWPs.

Experiments were conducted to quantify the N uptake of silage crops from land application of spent OWP materials. Results from OWP systems were compared to existing data on N recycling from conventional, slurry-based housing. The specific objectives were to:

Determine whether timber residues decomposed over a growing season when applied to grassland used for silage production

Evaluate STR from OWPs as a potential N fertiliser for silage production

Determine if land application of timber residue increases soil microbial activity or intercepts light from reaching plants to assist in understanding the mechanisms of N recycling from STR to grassland.

Evaluate effluent from OWPs as a potential N fertiliser source on grassland

Determine the sustainability of land application of OWP materials compared to slurry from conventional livestock housing.

In addition to improving the productivity of livestock farming, OWPs are a potential reuse of waste products from the forestry industry. Ireland's private forest estate is expanding at a rate of 12,500 ha per year (Gallagher and O'Carroll, 2001). Annual timber production from Irish forests is estimated to reach 3.7 million tons by 2015. The bulk of this material will be made up of thinnings. Determining a market for timber residues (wood chips and sawdust) from sawmills is one of the most important issues facing the Irish timber industry (Hoyne and Thomas, 2001). There are approximately 7 million cattle in Ireland (Dillon et al., 2003), and one-half to one ton of wood chip per animal is required for OWP use annually. Therefore, the potential market for timber residue in the dairy and beef industries is large. The use of OWPs also completes the cycle for forestry from growing trees to the utilization of those trees on the farm as the timber can be recycled onto farm land as a source of organic matter and nutrients.

Use of OWPs generates spent timber residue (timber and manure) and effluent (rain water and urine) that must be disposed of after each winter. Nutrients are retained in the STR and effluent and can be recycled within the farm system. Poor management of these potential nutrient sources has the capacity to negatively impact the environment (Smith, 2005). No research has been conducted on the management of spent OWP materials. The current recommendation for management of STR is to incorporate it into soil. However, grassland farmers rarely reseed their farm land and therefore incorporation of STR into soil is not a practical option. In addition, research on incorporation of wood shavings into soil demonstrates that incorporation may reduce the availability of soil mineralized N and limit crop production during the first growing season following application (Beachemin et al., 1992). Composting has also been suggested as a potential management strategy for STR to stabilize the OM and reduce the volume of STR. However, farmers are usually not capable of running a full-scale compost operation in conjunction with farming (Willrich, 1967). Active composting is labour-intensive and therefore not a cost-effective option for livestock farmers. In addition, research on the effect of composting wood shavings with manure has shown composting may increase N transformations such as NH_3 volatilization, nitrification and denitrification, leading to significant loss of N (Tiquia and Tam, 2000). Such losses may reduce the value of composted STR as an N fertiliser source for crop production.

Land application is the most common management of livestock bedding materials such as sawdust and shavings (Ward and Wohlt, 1996) and is the most practical management strategy for wastes associated with OWPs. There is increasing pressure on farmers to utilize the N from livestock wastes more efficiently in response to regulatory controls on N inputs (European Communities, 2006). Therefore, land application of spent OWP materials requires evaluation in terms of its N contribution and effect on crop yield. An understanding of the N recycling from OWPs will assist in determining whether or not this system is a sustainable method of housing livestock over winter.

METHODOLOGY

Objective 1. Determine whether timber residues decomposed over a growing season when applied to grassland used for silage production

The first objective of this project was to determine whether timber residues from forestry thinnings decomposed over a six-month growing season when applied to silage grassland. The temporal trends of timber residue sward coverage and timber residue weight were measured as two experiments described below. The research focused on the physical degradation of timber residue following land application. For land application to be an acceptable management strategy, timber residue needs to degrade so it is not ingested by livestock or contaminates silage crop. The results from this experiment have been peer-reviewed and accepted for publication in the Journal of Sustainable Agriculture (Augustenborg et al., *In*

Press).

The study was conducted at the Johnstown Castle Research Centre in south-east Ireland (52º17′ N, 6º30′ W) on a loam gley (hydric) soil. The temporal trends of timber residue sward coverage and weight were measured in the same field. The sward was managed the same for both experiments. The experimental sward was not grazed or fertilized in 2005 up to the start of the study. The grassland site was a permanent pasture originally sown with perennial ryegrass (*Lolium perenne*). In early May 2005, the grass on the site was cut to 55 mm. Inorganic fertilisers (N, phosphorus (P) and potassium (K)) were applied to the plots based on Teagasc advice for newly reseeded silage swards (Teagasc, 2004). Wood decay by fungi can be limited by N availability (Swift et al., 1979; Labosky et al., 1991; Hadas et al., 2004). Therefore, the N fertiliser rate advised for pastures with higher N requirements was used to improve N availability and potential timber residue degredation. Fertiliser was applied evenly across all the plots using a hand-pushed applicator. The N, P and K were applied at 125, 49 and 90 kg ha^{-1}, respectively on May 9; 100 and 90 kg ha^{-1} of N and K, respectively were applied on July 1; 100 kg ha^{-1} of N was applied on August 17; 100 kg ha^{-1} of N was applied on September 26. Grass was cut to 55 mm every eight weeks during the study period (June 24, August 10 and September 22) to replicate Irish agricultural practices for silage crop land (Teagasc, 2004). Climatic data for the period was recorded at the Johnstown Castle Research Centre weather station which was approximately one kilometre from the field plots.

Three timber application rates were selected for both experiments (3, 9 and 15 t ha^{-1}), which cover the range that might be applied annually on intensive cattle farms in Ireland. In practical application, timber residue from OWPs would be soiled with manure. However, STR (timber soiled with manure) is a variable product and its manure content would obscure degredation of timber. Manure mixed with the timber would have provided an immediate increase in available N, which would encourage microbial growth and enhanced decomposition of timber residues (Whitford et al., 1989; Hadas et al., 2004). For the purposes of this study, dry timber residue (without manure) was used. Excess inorganic N fertiliser was added to plots in order to enhance microbial growth and decomposition to mimic the effect of manure.

Experiment 1.1. Timber Residue Sward Coverage

This experiment examined the temporal trends in timber sward cover for three timber application rates over six-months. Six replicate plots (2 x 5 m) for each treatment were arranged in a randomized block design with a total of 18 plots. Forestry timber residue was applied to the plots manually on May 24, 2005. Timber residue coverage of the sward was measured bi-weekly using a point quadrat transit. A five meter transit line was placed along two sections of each plot and a sliding point quadrat on a tripod was randomly inserted into the sward at 15 locations along the transit line, giving a total of 30 quadrats per plot. The presence of forestry timber residue was recorded when timber was touched by the tripod at any of the 30 quadrats. The data generated for each point consisted of either a positive timber residue "hit" (= 1) or no hit (= 0) where only soil or grass was touched by the tripod. The forestry timber residue coverage for the plot was measured as a proportion of the number of positive timber "hits" for each plot encountered during each measurement period (= hits/30). Regression analysis (Shesken, 2004) was used to examine the effect of time on timber sward coverage for the three application rates.

1.2 Timber Residue Weight

This experiment measured the temporal trends in timber weight for three timber application rates over six-months. Timber residues were oven-dried, weighed and placed in plastic mesh (30 mm) bags. Litter bags were filled with forestry timber residue at rates of 17, 52 and 84 grams of dry weight timber per litter bag (equivalent to 3, 9 and 15 t ha^{-1}). Forty-five litter bags for each treatment were placed on the 2 x 5 m experimental plots (15 litter bags per plot). Plots were arranged in a randomized block design. The plots were cut to 55 mm before the litter bags were placed on the soil surface and held with metal stakes. The forestry timber residues were distributed evenly in each litter bag. Grass was able to grow through the bag mesh. Worms were observed penetrating the litter bags. One litter bag from each plot (three bags per treatment) was destructively sampled bi-weekly from May to November. The contents of the bag were oven dried (100ºC for 24 hours). The change in dry weight of the forestry timber residue was used to provide an estimate of decomposition. Linear regression was used to examine the effect of time on timber mass degradation for the three application rates.

Objective 2 Evaluate STR from OWPs as a potential N fertiliser for silage production
Spent timber residues (timber residues soiled with animal excreta) have the potential to be applied to land as a source of organic matter and nutrients (Hoyne and Thomas, 2001). Nutrients are retained in the STR and can be recycled within the farm system. There is increasing pressure on Irish farmers to utilize the N in manure more efficiently in response to regulatory controls on nutrient inputs (European Communities, 2006). Therefore, land application of STR from OWPs requires evaluation in terms of its N contribution and effect on crop yield. Objective two was to evaluate STR from OWPs as an N source for first and residual cut silage. Silage response to STR was compared to silage response to inorganic N fertiliser at rates from 0 to 125 kg ha^{-1} to confirm the N responsiveness of each site.

Two trials to evaluate the impact of STR on first cut DM yield and crop N were conducted between April and August 2004 and 2005. Three Irish sites were used in 2004 and two sites were use in 2005 (Figure 1). Site details, treatment application dates and harvest dates are summarized in Table 1. The grassland sites were generally perennial ryegrass (*Lolium perenne*) swards of more than five years old that had received no N fertiliser in the previous year to ensure N would be the limiting nutrient. The topography of all sites was gently rolling. In April of each year, the grass at each site was cut to 55 mm and the plots were marked. A dressing of phosphorus (P) and potassium (K) were applied at each site in both years at 35 and 150 kg ha^{-1} , respectively, to ensure crop growth potential was not restricted by an inadequate supply of these two nutrients (Teagasc, 2004).

All treatments were applied in April of each year. The list of treatments and N application rates for each year are described in Table 2. There were three STR treatments, five inorganic N fertiliser treatments as calcium-ammonium nitrate, and a control treatment where no N was applied. The treatments were arranged in a randomized block design with six replicates per treatment totalling 54 plots per site. The three rates of STR applied to treatment plots in this study were equivalent to 10, 30 and 50 t ha^{-1}. At the end of a 140 day winter, housing cattle on OWPs generates approximately 4.5 tonnes of STR per cow (French and Hickey, 2003). On an intensive Irish farm (2.5 cow ha^{-1}) STR would be applied to up to 50% of grassland. Therefore, a practical application rate for 100 ha farm would be 22.5 tonnes of STR per hectare. The five rates of inorganic N (25, 50, 75, 100 and 125 kg ha^{-1}) and the control (0 kg ha^{-1}) generated a response curve for silage yield and N uptake. This allowed conclusions to be made about the N responsiveness of the site and comparisons to be made between the STR and inorganic N fertiliser treatments. Swards were cut in June for first cut silage and the residual cut was taken in August. There was no STR or fertiliser applied following the first harvest.

2.1. Spent Timber Residue Analysis

Fresh STR was removed from an OWP in April 2004 and April 2005 and stored under cover for two weeks prior to application. A size characterization of timber residue particles was conducted on three samples of dry timber residue used in the OWP in both years using standard soil sieves (Table 3). Generally, the size of timber residue used ranged from 4-16 mm in length. Samples of fresh STR used in both years were chemically analyzed immediately prior to treatment application. Twenty shovelfuls of material were taken from a haphazard location and then composited into one sample. Three sub samples were taken from the composite pile for DM and nutrient (total N, P and K) analyses. The DM of the STR was determined by drying samples at 105 °C for 16 hours. For nutrient analyses, samples were oven-dried at 80ºC for16 hours, ground to pass through a 2 mm sieve and then extracted. Most of the timber in the STR did not pass through the 2 mm sieve, leaving primarily manure for the nutrient content analysis. Therefore, the digestion procedure was able to completely eliminate any remaining particles. Total P and K were determined for each sample (2.0 g air-dry weight) following digestion with H_2SO_4 and H_2O_2 and using a selenium catalyst (Bryne, 1979). Total P was determined spectrophotometrically following molybdo-vanadate color development using a Chemilab auto-analyzer. Total K was determined in the digests by flame AAS on a Varian AA-400 instrument. Total N was determined in the reaction of ammonia with salicylate and dichlorisocyanurate (DIC) in alkaline solution using a Chemilab auto-analyzer (Bryne, 1979).

STR may contain heavy metals in concentrations at levels that may preclude application to agricultural land based on standards set under regulations covering the use of sewage sludge in agriculture (European Communities, 1998). In 2004, STR was analyzed for heavy metals including cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), manganese (Mn), nickel (Ni), lead (Pb) and zinc (Zn). Total Cd, Cr, Cu, Mn, Ni, Pb and Zn were determined in dried sieved samples following aqua-regia digestion on a 20 place Gerhardt heavy metal digester. The digestion procedure was able to completely eliminate any remaining particles. Analysis was carried out by AAS using a Varian AA-400 instrument (McCormack, 2002). Total Hg was determined by cold vapor atomic fluorescence following aqua-regia digestion using stannous chloride as reductant (Corns and Stockwell, 1996; McCormack, 2002).

2.2. Crop Measurements and Analysis

For each harvest date, the grass was collected from each plot and weighed using a plot harvester cutting to 55 mm. The cut herbage removed from each plot was sub-sampled (1 kg) for DM yield and total N concentration determinations. The grass samples were sub-sampled in the laboratory and oven-dried at 95ºC for 16 hours. The dried grass samples were ground in a Christy and Norris laboratory mill to pass a 0.2 mm sieve for total N analysis. A 0.5 g oven dry weight sub sample was transferred to a 100 ml Gerhardt digestion tube for the standard Teagasc digestion procedure (McCormack, 2002). Total N was determined in the reaction of ammonia with salicylate and DIC in alkaline solution using auto-analyzer (Bryne, 1979; Chemilab Instruments Ltd., 1985; McCormack, 2002).

2.3. Statistical Analysis

All statistical tests were performed in SPSS 12.0.1 for Windows (SPSS, Chicago, IL, USA). Least squares regression analysis was applied to the relationships between DM yield and N uptake at each harvest for N application rates. Regression analyses and determination coefficients between the N applied and crop response were obtained (Pommel, 1995). Quadratic ($Y = a + bX + cX^2$) equations were used in regression analysis, where “Y” represents the silage DM yield or N response; “X” represents the N applied; and “a”, “b” and “c” represent regression coefficients.

Objective 3. Determine if land application of timber residue increases soil microbial activity or intercepts light from reaching plants to assist in understanding the mechanisms of N recycling from STR to grassland.

It was hypothesized that if the STR had a negative effect on crop DM yield and N response, it would be through either immobilization of manure nutrients or by a physical shading effect of the timber. Therefore, a third objective was to elucidate the impact of *dry* timber residue (not soiled with manure) on silage DM yields to separate the nutrient effect of manure from the shading effect of timber. The experiment was conducted at the Johnstown Research Centre (Figure 1) on a coarse loam gley (hydric) soil. The grassland site had a perennial ryegrass (*Lolium perenne*) sward that had not been grazed or fertilized for the 2005 season. In May 2005, the grass on the site was cut to 55 mm and 18 plots (2 m x 5 m) were marked. Inorganic fertilisers (N, P and K) were applied evenly to the plots based on Teagasc advice to ensure an adequate nutrient supply for first, second and third cut silage crops (Teagasc, 2004). All treatments received the same amount of N, P and K in the form of inorganic fertilisers. The N, P and K were applied at 125, 49 and 90 kg ha^{-1}, respectively on May 9th for first cut; 100 and 90 kg ha^{-1} of N and K, respectively were applied for second cut on July 1st; 100 kg ha^{-1} of N was applied for third cut on August 17th. The N fertiliser strategy was to ensure N supply was not limited.

Dry timber residue treatments were applied by hand on May 24 to plots that had been cut to 55 mm. There were three dry timber residue treatments and a control treatment which received no timber residue. The treatments were arranged in a randomized block design with six replicates per treatment totalling 24 plots. The three dry timber residue treatments were applied at 3, 9 and 15 t ha^{-1}. Dry timber application rates were calculated based on previous research on housing cattle on OWPs which used approximately 1.1 tonnes of dry timber residue per cow (French and Hickey, 2003). A practical application rate for a 100 ha farm would be 5.5 tonnes of dry timber per hectare. The plots were harvested on June 24 for first cut silage; August 10 for second cut silage; and September 22 for third cut silage. There was no reapplication of dry timber following any of the silage cuts.

Objective 4. Evaluate effluent from OWPs as a potential N fertiliser source on grassland

The fourth objective was to determine if effluent from OWPs can be utilized as potential N fertiliser source on Irish grassland. Farm system fertiliser management must account for nutrients from effluent land-application to prevent nutrient surpluses reaching ground and surface waters. (Ryan, 1991; Chadwick and Chen, 2002; Rodgers et al., 2003; Gibbons et al., 2006). Appropriate management of OWP effluent requires understanding the N content of effluent and its effect on crop yield. This research quantified the N efficiency of OWP effluent by measuring the DM yield and plant N response of first cut and residual cut silage to three rates of OWP effluent. The results were compared to the response from inorganic N fertiliser and cattle slurry (manure and urine) to determine the value of OWP effluent as an N source for first and residual cut silage.

Trials to evaluate the impact of effluent on silage crop DM yield and crop N were conducted from April to August in 2004 and repeated in 2005. In 2004, three locations in Ireland were used: Moorepark in the Southwest (Latitude 52º09’ N, Longitude 08º15’ W); Johnstown in the Southeast (Lat. 52°18' N, Long. 6°29' W) and Grange in the Northeast (Lat. 53º31’ N, Long. 06º40’ W). Only the Moorepark and Johnstown sites were use in 2005, where new plots were selected for the second year. Site details, treatment application dates and harvest dates are summarized in Table 1.

The grassland sites were generally perennial ryegrass (*Lolium perenne*) swards that had not received N fertiliser in the previous year. The topography of at all sites was gently rolling. In April of each year, the grass at each site was cut to 55 mm and the plots were marked. Phosphorus (P) (35 kg ha^{-1}) and potassium (K) (150 kg ha^{-1}) were applied at each site prior to treatment application. P and K application rates were based on Teagasc agronomic advice to ensure crop growth potential was not restricted by an inadequate supply of either nutrient (Teagasc, 2004).

All treatments were applied in April of each year. The list of treatments and N application rates for each year are described in Table 4. There were three effluent treatments (15, 30 and 60 tonnes ha^{-1}), five inorganic N fertiliser treatments (25, 50, 75, 100 and 125 kg ha^{-1}) as calcium-ammonium nitrate, and a control treatment where no N was applied. In 2004, additional plots of slurry at three application rates (3, 9 and 15 tonnes ha^{-1}) were included in each trial. The slurry application rates were chosen to make N supply from effluent and slurry treatments similar. The treatments were arranged in a randomized block design with six replicates per treatment, totalling 72 plots per site in 2004 and 54 plots per site in 2005. Effluent application rates were selected based on previous results by French and Hickey (2003) which demonstrated that 5,901 kg of effluent per steer is generated on an OWP in Ireland over a 151 day winter. This level of effluent production would require effluent land application at rate of 15 to 30 tonnes ha^{-1} on an intensive Irish dairy farm. The N applied for effluent treatments varied between years due to the variability in N concentrations of the effluent used each year. There was no re-application of effluent, slurry or inorganic N fertiliser over the course of the experiments. Swards were cut in June for first cut silage and in August for residual cut silage.

4.1 Effluent and slurry analysis

Effluent and cattle slurry were obtained from covered storage tank at Teagasc's Grange Research Centre in April. Samples of effluent and slurry were analyzed for total N, P and K immediately prior to land application. In addition to the effluent applied in these trials, effluent samples collected in March 2005 from six other OWPs throughout Ireland were analysed for comparison. Total oxidized N, NO_3-N, NH_4-N, P and K were measured colorimetrically using a Konelab 30 discrete analyzer. Total N, P and K fractions were determined colorimetrically by continuous flow analysis following oxidative digestion with potassiumperoxodisulphate. Samples were digested for 30 minutes at 121 ºC in an autoclave according to the method of Ebina et al. (1983).

For cattle slurry analyses, samples were oven-dried at 80ºC for 16 hours and extracted. Total P and K were determined for each sample (2.0 g air-dry weight) following digestion with H_2SO_4 and H_2O_2 and using a selenium catalyst (Bryne, 1979). Total P was determined spectrophotometrically following molybdo-vanadate color development using a Chemilab auto-analyzer. Total K was determined in the digests by flame AAS on a Varian AA-400 instrument. Total N was determined in the reaction of ammonia with salicylate and DIC in alkaline solution using a Chemilab auto-analyzer (Bryne, 1979). To determine DM content, slurry was dried at 105 °C for 16 hours.

4.2 Crop measurements and analysis

For each harvest date, the grass from each plot was cut to 55 mm and weighed using a plot harvester. The cut herbage removed from each plot was sub-sampled (1 kg) for DM and N concentration. The grass samples were sub-sampled in the laboratory and oven-dried at 95ºC for 16 hours. The dried samples were ground in a Christy and Norris laboratory mill to pass a 0.2 mm mesh for total N analysis. A 0.5 g oven dry weight sub-sample was transferred to a 100 ml Gerhardt digestion tube for a standard digestion procedure (McCormack, 2002). Total N was determined in the reaction of ammonia with salicylate and DIC in alkaline solution using auto-analyzer (Bryne, 1979; Chemilab Instruments Ltd., 1985; McCormack, 2002).

4.3 Statistical Analysis

All statistical tests were performed in SPSS 12.0.1 for Windows (SPSS, Chicago, IL, USA). Least squares regression analysis was applied to the relationships between DM yield and N uptake at each harvest for N application rates. Regression analyses and determination coefficients between the N applied and crop response were obtained. Linear ($Y = a + bX$) and Quadratic ($Y = a + bX + cX^2$) equations were used in regression analysis, where "Y" represents the silage DM yield or N response; "X" represents the N applied; "a", "b" and "c" represent regression coefficients. The fertiliser value of the N in the effluent and slurry treatments was compared with inorganic N fertiliser using formulae developed by McLaughlin and Champion (1987) and Pommel (1995). These formulae calculate the efficiency (%E) of effluent or slurry N treatments relative to inorganic N fertiliser in terms of DM yield responses from the derived quadratic responses as follows:

$\%E = (c \times X^2 + b \times X)_{\text{treatment}} / (c \times X^2 + b \times X)_{\text{inorganic}} \times 100$

Objective 5. Determine the sustainability of land application of OWP materials compared to slurry from conventional livestock housing.

The EU Nitrates Directive (91/676/EEC) aims to reduce N contamination of water supplies by restricting rates of inorganic N fertiliser applied to grassland farms. Maximum fertiliser N rates for grassland receiving livestock manures are based on the assumption that, by 2010, N from manure will be utilized at 40% efficiency to reduce N loss from agricultural systems to the environment. Failure to meet this efficiency will result in suboptimal rates of available N (fertiliser and slurry), which could result in losses in farm productivity. The overall objective of this research was to compare OWPs to conventional, slurry-based cattle housing with respect to inorganic N fertiliser requirements for spring silage production. Before OWPs can be widely implemented, they must be evaluated in terms of farm-system N efficiency so that optimized N recycling of livestock manure in compliance with EU regulations can be assured.

This study determined the combined effect of land application of STR and effluent from OWPs on silage yield and inorganic N fertiliser requirements by up-scaling individual component research findings to farm level. The motivation for this research was to determine which livestock wintering system is more effective to comply with 2010 EU legislation on inorganic N fertiliser use.

5.1. Outline of model

A nitrogen-flow model was constructed to compare manure management from different livestock housing systems. The framework was developed as a static simulation model to compare the land application of livestock materials from an OWP system (effluent and STR) to slurry from conventional livestock housing. A schematic representation of model calculations is shown in Figure 2, where shaded boxes denote mathematical outputs. Three N management scenarios were developed. First, the silage DM yield was held constant for all systems in order to determine how much inorganic N fertiliser would be needed to achieve maximum first cut silage yield in each system based on current EU regulations. Second, the effect on first cut silage yield for each system when inorganic N fertiliser was restricted was determined based on 2010 EU regulations. The costs associated from each of these outputs were established. Finally, the N efficiency from each housing system was determined.

The model parameters are described in Table 5. The model was applied to an intensive Irish dairy farm with a stocking rate of 2.5 LU per hectare. Forty percent of the farm area was allocated for first cut silage production (Dillon and Crosse, 1997). The time that animals were kept on OWPs or in conventional housing was based on an average Irish winter of 150 days. The total rainfall in that period (November - March) was estimated at 793 mm (European Communities, 2006). It was assumed all STR, effluent and slurry would be applied prior to first cut.

5.2 Livestock materials

The N concentrations, N efficiencies and fertiliser replacement values of the livestock wastes from each system are described in Table 6. The mathematical formulae for this research are summarized in Table 7. Nitrogen efficiency was defined as N output divided by N input based on data from previous experiments on land application of fertiliser, STR and effluent. The N efficiencies of STR and effluent were determined as part of objectives two and four, respectively. The slurry N concentration and N efficiencies of two slurry application technologies were based on Nitrates Directive determination on nutrient content in slurry (European Communities, 2006). The current N efficiency of slurry via SP technology (25%) does not meet the EU Nitrates Directive requirement of 40% N efficiency from slurry by 2010. To address this issue, we included an additional livestock winter housing system which assumed that in 2010 a best available technology (BAT), such as shallow injection or trailing shoe systems, will achieve this requirement. Fertiliser replacement values (FRVs), or fertiliser equivalencies, were defined as the ratio of the N efficiency from livestock waste to the N efficiency from inorganic N fertiliser.

5.3 Simulation procedure

Two livestock housing systems were established. The variables for each system are presented in Table 8. The OWP system was based on an OWP with a stocking rate of 15 m^2 LU^{-1}, which is the average stocking rate of OWPs in the United Kingdom (Smith, 2005). The volume of spent timber produced in this system was calculated from the average amount of dung produced (Table 5) plus the amount of clean timber applied to an OWP over a 150 day winter. Clean timber is typically applied to OWPs at a rate of 100 kg m^{-2} with one additional dressing of 30 kg m^{-2} during winter to maintain cleanliness (French and Hickey, 2003). The volume of effluent produced in this system was calculated from the average amount of urine produced plus the average amount of rainfall on the OWP over a 150 day winter (Table 5). The STR and effluent application rates were calculated based on the amount of STR and effluent produced over winter divided by the silage land area. The N applied from STR and effluent were calculated based on the STR and effluent application rates multiplied by the N concentration of each material (Table 6).

Land application of slurry from conventional livestock housing was evaluated for comparison with the OWP system. The volume of slurry produced in the conventional housing system was calculated from the average amount of dung and urine produced (Table 5) over a 150 day winter. The slurry application rate was calculated based on the amount of slurry produced divided by the silage land area. This value was multiplied by the average N concentration of slurry (Table 6) to determine the rate of N applied from slurry. Two slurry land application methods (SP and BAT) were included as systems for the conventional, slurry-based housing system. Nitrogen efficiency values were used to calculate FRVs for each application technology. The N efficiency of SP slurry application was based on Teagasc nutrient advice for spring slurry application (Coulter, 2004). The N efficiency of the BAT was based on the Nitrates Directive requirement that slurry N efficiency equal 40% by 2010 (European Communities, 1991). The fertiliser equivalent rates from slurry, effluent and STR (Table 9) were calculated by multiplying the N applied from each material by the FRV of each application method.

5.4 Maximum Silage Yield Scenario

The optimal inorganic N fertiliser required to achieve maximum first cut silage yield was calculated based on inorganic N fertiliser response curves generated from the experiment described as part of objective two. The fertiliser response curve from the Southeast location (Latitude 52°09’ N; Longitude 08°15’ W) provided a method of determining the optimum rate of fertiliser application and maximum first cut silage yield for this particular site. Regression was used to model the crop response to increasing rates of inorganic N fertiliser. The equations for first cut DM yield and N uptake responses are presented in Table 10. Silage DM yield followed a quadratic response:

$Y = a + bX + cX^2$

Where Y represented the silage DM yield; X represented the N applied; and “a”, “b” and “c” represented regression coefficients. The sward reached N saturation at an application rate of 100 kg N · ha^{-1} for first cut silage, which was therefore considered the optimal N application rate for this sward. The N uptake followed a linear response:

$Y = a + bX$

Where “Y” represented the herbage N uptake; “X” represented N applied; “a” was the slope and “b” was the y-intercept. The quantity of inorganic N fertiliser required for each system was determined by subtracting the FRV from livestock wastes from the optimum N application rate for each site. The cost of inorganic N fertiliser was estimated at 800 euro per ton of N from calcium-ammonium nitrate (Central Statistics Office Ireland, 2005).

5.5 2010 Nitrates Directive Scenario

The effect of restricted inorganic N fertiliser on first cut silage yield was calculated based on the Nitrates Directive limit stating that a 40% of allowable N input must come from livestock manure by 2010 (European Communities, 1991). The annual suggested N input for an intensive livestock farm in Ireland is 320 kg ha^{-1}, approximately 27% (87 kg ha^{-1}) of which would be applied from January to March for first cut silage growth (Humphreys et al., 2004). The Nitrates Directive stipulates 40% of N in animal manure must be accounted for and deducted from the maximum allowable N input. For each housing system, the amount of N from animal manure that had to be accounted for was calculated by multiplying the N concentration of manure (Table 6) by the material application rate (Table 8) multiplied by 40%. For the OWP system, only N from STR was input into the calculation since regulations do not stipulate that N from effluent must be considered in the farm fertiliser regime. The maximum allowable inorganic N fertiliser for the OWP system was 60 kg ha^{-1} for first cut silage, while for the conventional systems it was 27 kg ha^{-1} due to the fact that the slurry application rate (30 tonnes ha^{-1}) was almost twice as high as the STR application rate (16 tonnes ha^{-1}) and because the N concentration of STR was lower than that of slurry (Table 6). The total N contributed to silage crop was calculated by adding the maximum allowable inorganic N fertiliser (60 kg ha^{-1} for OWP system and 27 kg ha^{-1} for conventional system) to the total fertiliser equivalent rate from livestock wastes for each system (Table 9). The first cut herbage yield (tonnes DM · ha^{-1}) was determined using the inorganic N fertiliser response curve described in section 2.4, where the X variable was the sum of inorganic N fertiliser applied plus the fertiliser equivalent values from livestock waste (Table 9). The cost of additional silage was estimated at 145 euro per tonne of silage DM (Donworth, 2006).

5.6 System Nitrogen Efficiency

The third model output determined the N accounted for following land application of OWP materials compared to slurry land application for first cut silage. System N inefficiency was calculated as a percentage of total N applied where

System N Efficiency (%) = (Total N uptake / Total N applied) x 100.

Total N uptake was defined by the equation:

Total N uptake = Σ (N applied $_{\text{material 1}}$ * N efficiency $_{\text{material 1}}$) + (N applied $_{\text{material 2}}$ * N efficiency $_{\text{material 2}}$)…

where the materials were STR, effluent and inorganic N fertiliser for the OWP system or slurry and inorganic N fertiliser for the slurry-based housing system. Total N applied was the sum of inorganic N fertiliser applied plus STR and effluent for the OWP system or inorganic N fertiliser applied plus slurry N applied for the conventional housing systems.

RESULTS

Objective 1. Determine whether timber residues decomposed over a growing season when applied to grassland used for silage production

The average initial sward coverage for forestry timber residue application rates of 3, 9 and 15 tonnes ha^{-1} at the start of the experiment were 26%, 48% and 60%, respectively (Figure 3). The initial timber residue coverage obeyed a spatial Poisson distribution when analysed using a chi-squared test ($p < 0.05$). To ensure grass harvesting did not result in removal of timber residue from the sward, coverage measurements were taken immediately before and immediately after grass harvesting on June 24. A paired sample t-test (Shesken, 2004) demonstrated no significant difference ($p < 0.05$) between timber sward coverage proportions before and after grass harvesting for all three application rates. Grass harvesting did not interfere with timber sward coverage.

Experiment 1.1. Timber Residue Sward Coverage

Immediately after application, timber residues were clustered together with some overlap of the timber chips. Overlapped chips were counted as only one “hit” using the method described for this experiment. Over time, timber residues dispersed over the sward, causing the timber residue coverage of the sward to appear to increase during the first ten weeks of the study. Given the dispersion of timber residues over time, timber sward coverage was fitted to a quadratic curve as a function of time for the three application rates in the following form:

$C = a + bT + cT^2$

Where C is the proportion of sward coverage, T is time entered as week, and a, b and c are modelled coefficients. Results of these curve fits are tabulated in Table 11. Regression coefficients (R^2) ranged from 0.39 to 0.46. The forestry timber residue cover of the sward decreased significantly ($p < 0.001$) over the measurement period for all three application rates. Average sward cover for the three treatments declined to 8%, 36% and 34%, respectively by the end of the 182 day measurement period (3).

Experiment 1.2. Timber Residue Weight

The weight of timber residues did not decrease over time for any of the application rates. Timber residue weight was applied to a linear curve as a function of time for the three application rates in the following form:

$Y = mX + b$

Where Y is the timber mass degradation, X is time entered as week, m is the slope and b is the y-axis intercept. Model coefficients are tabulated in Table 11. The weight of timber residues increased significantly ($p < 0.05$) for the all three application rates over the growing season. Regression coefficients (R^2) ranged from 0.12 to 0.21. Since the bags holding the timber residue were permeable, soil, grass and organisms were able to enter the bags and attach to the timber. After manually removing much of the material attached to the timber and drying the residue at 100ºC overnight, soil particles remained on the timber. These soil particles resulted in an increase in weight of up to 5% of the initial timber weight and are responsible for the increase in weight of the timber residue over time.

Objective 2. Evaluate STR from OWPs as a potential N fertiliser for silage production

2.1. Spent Timber Residue Analysis

The results for DM and nutrient (total N, P and K) analysis of samples of STR prior to land application in 2004 and 2005 are shown in Table 12. No other published data exists on nutrient content of STR so comparisons can not be made on the relevancy of these results to other STR. Therefore, nutrient values of slurry (urine and faeces) from conventional cattle housing systems in Ireland are presented in Table 12 for comparison. Details of the collection and analysis of this slurry are described in objective four. The metal content of the STR was less than one percent of the prescribed regulatory limits for each metal (Cd, Cr, Cu, Mn, Ni, Pb and Zn) based on statutory limits set for the use of sewage sludge in agriculture (European Communities, 1998). The results of the metal analysis and regulatory limits are presented in Table 13.

2.2. Inorganic Fertiliser Response

A summary of the first cut DM yield responses to the inorganic fertiliser N applications is presented in Figure 4. With the exception of the Johnstown site in 2005, the results show a significant DM yield response ($p<0.01$) to increasing fertiliser N applications. A significant responses ($p<0.01$) of first cut silage N to increasing fertiliser N application occurred in all five trials (Figure 5). Silage N concentrations from the control treatments (no N applied) ranged from 100 to 150 $g\ N \bullet g\ DM^{-1}$ in 2004 and 2005 at all locations. The effect on silage DM yield and N response of a residual cut taken from all plots in mid-August were also determined. The results are presented in Figure 6. With the exception of Moorepark in 2005, there was a significant linear DM response ($p<0.05$) to increasing fertiliser N applications. No significant residual cut herbage N response to increasing application rates of inorganic N fertiliser was observed in four out of five trials. Only Moorepark in 2004 showed significant results for residual cut silage N concentration

2.3. Spent Timber Residue Response

The first cut silage DM yield response for the three STR application rates for all trials are shown in Figure 4. There was no significant first cut DM yield response to STR at any of the three application rates. The DM yield for the STR treatments were similar to those of the control (N applied = 0) for all trials. For first cut silage N response, a weak significant effect ($p<0.01$) was observed for the Moorepark site in 2004. However, all other trials showed no significant difference in first cut silage N response with increasing STR application rates so the results are not presented. For the residual cut DM yield response to the STR, only the Johnstown 2004 trial demonstrated a significant negative response ($p < 0.05$) in residual cut DM yield. Residual cut silage DM yield for the highest STR at Johnstown in 2004 were approximately 35% lower than the control. All other trials showed no significant difference in residual cut silage DM yield with increasing STR application rates so the results are not presented.

Objective 3. Determine if land application of timber residue increases soil microbial activity or intercepts light from reaching plants.

The effect of dry timber application on first, second and third cut silage DM yields are shown in Figure 7. Grass growth changes seasonally, so yields will always be lower as the summer progresses. Pearson product-moment correlation indicated a significant negative relationship ($p < 0.01$) between timber application rate and crop DM yield for first cut silage. Second and third cut silage DM yields and first, second and third cut crop N uptake were not responsive to treatments.

Objective 4. Evaluate effluent from OWPs as a potential N fertiliser source on grassland

4.1. Effluent and slurry analysis

The results from nutrient analysis of OWP effluent prior to its land application in 2004 and 2005 are shown in Table 14. The effluent used in the 2004 trials contained 458 mg L^{-1} of total N, approximately 59% of which was in the plant-available, inorganic N form. The effluent used in the 2005 trials contained 343 mg L^{-1} of total N, approximately 63% of which was in the plant-available, inorganic N form. The nutrient content from effluent samples from six other OWPs throughout Ireland are also described in Table 14. The total N from these samples ranged from 97 to 810 mg L^{-1} and contained 25 to 95% plant-available, inorganic N. The ammonium N content ranged from 24 to 424 mg L^{-1} of NH_4-N. Cattle slurry used in the 2004 trials contained 3.1 g kg^{-1} of total N.

4.2 Crop response to effluent

Figure 8 illustrates the first cut silage DM yield for the three effluent application rates compared to the inorganic N fertiliser response in 2004 and 2005 at three sites. In 2004, there were significant ($p < 0.05$) DM yield responses to increasing effluent application for first cut silage on all sites. Responses followed a linear model. The regression coefficients are displayed in Table 15. Contrastingly, in 2005 no significant response was observed in first cut silage N response to increasing effluent application in either trial.

To determine whether the response to effluent treatments was similar to the response to inorganic N fertiliser for first cut silage yield, an F-test was employed to compare regressions,

$$F = \frac{[RSS(a,b) - (RSS(a_1,b_1) + RSS(a_2,b_2))]/2}{s^2}$$

Where RSS is the residual sum of squares, "a" is the intercept, "b" is the slope, and s^2 is sample variance. The subscripts 1 and 2 refer to the effluent or fertiliser, respectively, and the un-numbered subscripts refer to the effluent and fertiliser data combined. A p-value of less than 0.01 was considered evidence of a statistically improved fit. In all five trials, the effluent and fertiliser regression lines were not significantly different from each other for first cut DM yield response.

When residual cut DM yield was analyzed, none of the trials demonstrated a significant yield response ($p < 0.05$) to increasing effluent application. For residual cut N uptake, the Moorepark trial in 2005 was the only trial which demonstrated a significant response to increasing effluent application. This may indicate a delayed response to effluent since the site showed no significant response in the first cut. The model coefficients describing the effect of effluent application on residual cut crop N uptake response for Moorepark in 2005 are displayed in Table 15.

Fertiliser equivalents or efficiencies of effluent were calculated for trials where the results of both the effluent treatments and the inorganic N fertiliser treatments were statistically significant ($p<0.05$). The fertiliser efficiencies calculated for first cut DM yield for 2004 trials are displayed in Table 16. The efficiency of OWP effluent ranged from 74 to 90% at the highest application rate (27.6 kg N ha^{-1}) compared to inorganic fertiliser for first cut silage DM yield.

4.3 Crop response to slurry

Figure 8 illustrates the 2004 first cut silage DM yield response to slurry treatments. The Moorepark and Grange trials demonstrated significant ($p < 0.05$) DM yield response to increasing slurry application for first cut silage. First cut DM yield responses followed a quadratic model, the coefficients of which are displayed in Table 15. For the residual cut N response, only the Johnstown 2004 trial demonstrated a significant negative ($p < 0.05$) silage N response from increasing slurry applications. All other trials showed no significant silage N response in the residual cut.

Fertiliser equivalents or efficiencies of slurry were calculated for trials where the results of both the slurry treatments and the inorganic fertiliser treatments were statistically significant ($p<0.05$). The fertiliser efficiencies calculated for first cut DM yield for 2004 trials are displayed in Table 16. N uptake from slurry was 35 to 97% as efficient as the equivalent quantity of N applied via inorganic N fertiliser for the Grange 2004 trial and 0 to 35% as efficient as inorganic N fertiliser for the Moorepark 2004 trial.

Objective 5. Determine the sustainability of land application of OWP materials compared to slurry from conventional livestock housing.

5.1. Livestock material application

The material application rates and the N applied from each material are presented in Table 8. These calculations were based on measured data for N concentrations of STR and effluent and Nitrates Directive data for N concentration of slurry (Table 6). The STR was applied at a rate of 16 tonnes ha^{-1} (68 kg $N \cdot ha^{-1}$). The effluent was applied at a rate of 25 tonnes ha^{-1} (10 kg $N \cdot ha^{-1}$). The slurry was applied at a rate of 30 tonnes ha^{-1} or 148 kg $N \cdot ha^{-1}$. The fertiliser equivalents of each livestock waste material for the simulated dairy farm are presented in Table 9. None of the N applied from STR was taken up by herbage but effluent application was equivalent to 8.8 kg ha^{-1} of N from inorganic fertiliser. Slurry applied via the SP method was equivalent to 51 kg ha^{-1} of N from inorganic fertiliser, while slurry applied via BAT was equivalent to 81 kg ha^{-1} of the N from inorganic fertiliser.

5.2 Maximum Silage Yield Scenario

The inorganic N fertiliser required to achieve maximum first cut silage yield for each livestock housing system for a field in Southeast Ireland in 2004 is presented in Table 17. For this location, the BAT slurry-based system required the lowest input of inorganic fertiliser N (19 kg ha^{-1}) and was therefore the optimal system in terms of N fertiliser cost. When a SP system was used for slurry land application, an additional 30 kg ha^{-1} of inorganic N fertiliser was required to achieve optimum first cut silage yield compared to BAT. The OWP system resulted in inorganic N fertiliser requirements of 91 kg ha^{-1}. An additional 72 kg $ha^{-1}$of inorganic N fertiliser must be added to achieve maximum first cut silage yield using the OWP system instead of a slurry-based BAT system. This would amount to a total cost of €1,388 for inorganic N fertiliser for the OWP system to achieve the same silage yield as the conventional BAT system for the total silage area in the current research.

5.3 2010 Nitrates Directive Scenario

The effect of restricted inorganic N fertiliser based on 2010 Nitrates Directive limits on first cut silage yield is presented in Table 18. The BAT slurry-based system yielded the most herbage for first cut silage (7.6 tonnes $DM \cdot ha^{-1}$) and was therefore the optimal system in terms of N fertiliser cost. When a SP system was used for slurry land application, 200 kg less DM per hectare was yielded compared to BAT. The OWP system resulted in first cut herbage yields of 7.3 tonnes $DM \cdot ha^{-1}$. An additional €44 per hectare would be required using the OWP system in order to purchase the additional silage that would have been generated from the conventional BAT system.

5.4 System Nitrogen Efficiency

Total N applied and N uptakes from each system are displayed in Table 18. The lowest rate of total N applied (138 kg ha^{-1}) and N uptake (53 kg ha^{-1}) occurred in the OWP system. The SP and BAT slurry systems had the same total N application (175 kg ha^{-1}) but N uptake from the BAT system was 30 kg ha^{-1} greater than the SP system. The system N efficiency was greatest in the slurry BAT system (58%) and lowest in the OWP system (40%). The SP system was 17% less efficient than the BAT system and 2% more efficient than the OWP system.

DISCUSSION
(relevance of the results, comparison to other work)

Objective 1. Determine whether timber residues decomposed over a growing season when applied to grassland used for silage production

The proportion of timber coverage on the sward for three application rates over one growing season decreased significantly ($p < 0.001$) over the measurement period. The model coefficients b and c presented in Table 11 are nearly identical for the three application rates. Therefore, we conclude changes in timber residue sward coverage over time were independent of application rate. Sward cover for the three timber application rates declined by an average of 18%, 12% and 26% by the end of the measurement period (Figure 3). These results indicate up to one quarter of the timber residue applied to the sward either decomposed or was incorporated into soil over the growing season.

Rainfall for the May to December period was 662 mm; 11% more than the 25-year (1980-2005) mean for this period recorded at Johnstown Castle (Wexford, Ireland). 572 mm of rain was recorded in the 182 day period. Figure 9 displays the daily rainfall patterns during the period from application until end of experiment. In general, rainfall is not considered a limiting factor to decomposition in Ireland (Swift et al., 1979). Decomposition has been demonstrated to increase with increasing precipitation (Austin and Vitousek, 2000). Since rainfall during the study period was above the 25-year average, moisture content was not considered a limiting factor for timber degredation.

The temporal measurements in the weight of forestry timber residue (Figure 10) demonstrate a significant ($p<0.05$) increase in weight over time due to soil attachment to the timber and are therefore not accepted experimental results. The intercepts and slopes of the modeled results in Table 11 follow a 3:9:15 ratio like that of the application rates. This indicates changes in timber weight over time were independent of application rate. We conclude that since no significant decrease in weight of timber residue over the growing season was detected, timber residue did not decompose during the growing season while lying on grass sward in permeable litter bags.

Since timber residue in litter bags did not decompose, it can be inferred that timber residue lying directly on the sward in the sward coverage experiment did not decompose either. Therefore, the timber residue that was no longer present on the sward surface at the end of the coverage experiment must have been incorporated into the soil. While 12-26% of timber residue applied to grassland was incorporated into soil, over 88-74% of timber residue remained on the sward surface at the end of the study. Limited studies exist on the decomposition of timber residues on land. A study by Whitford et al. (1989) on degraded rangeland demonstrated timber chips were still present as visible mulch at the end of a two year study. Duryea et al. (1999) demonstrated only 3-7% decomposition of pine bark chippings after one year in a ploughed open field in Florida. Long term accumulation of timber residue on grassland may increase risk of ingestion of timber residues by grazing livestock, silage contamination or crop yield reduction. Methods to accelerate degradation, such as composting or incorporating timber residues into soil, should be considered if land application of timber residue is used as a management strategy for STR.

Several studies have demonstrated some degree of initial net N immobilization following timber residue application to soil (Ashworth and Harrison, 1983; Lalande et al., 1998; Blumfield and Xu, 2003; O'Connell et al., 2004). As microbes decompose timber residues, they consume N and thus immobilize N and reduce soil nutrient availability (Swift et al., 1979; Hadas et al., 2004). In a cultivated agricultural environment, N immobilization from the addition of high carbon (C):N ratio materials such as timber is undesirable (Whitford et al., 1989). However, when a majority of the forestry timber residue applied to land has decomposed, it should begin to release N and increase soil nutrient availability once again. Soumare et al. (2002) found a large decline in foliar N concentration in the first crop of tomatoes after timber mulch application, followed by large increase in foliar N in a subsequent crop one year later. This indicates soil nutrients have the ability to equilibrate following one application of timber residues to crop land. However, no studies have been conducted on the effect of repeated application of timber on crop land. While the physical degradation of timber residue illustrated in this experiment indicates a single application of timber residue to grassland may be an appropriate management strategy for out wintering pad materials, the sustainability of this system needs to be tested in terms of its repeated application of the material on crop land and its impact on soil fertility and crop production.

Objective 2. Evaluate STR from OWPs as a potential N fertiliser for silage production

The main objective of this research was to evaluate spent timber residue as a nitrogen source for silage. The positive response to inorganic fertiliser for all trials except Johnstown in 2005 indicated four out of five of the experimental sites were N limited. Results from this study demonstrate that there was no silage DM or N response to N in STR at application rates from 10 to 50 t ha^{-1}. All first cut DM yield responses to STR were similar to the control (no N applied) responses. This may be explained by one or a combination of the following hypotheses. First, most of the N in manure is in the organic form and must be mineralized before becoming crop available. Irish agronomic advice for farm yard manure applied to grassland in spring indicates that this manure does not contribute to the N supply for first cut silage (Teagasc, 2004). The results suggest the four-month growth measurement period of this study was not sufficient for mineralization of N from STR. A second possible hypothesis to explain the absence of a first cut DM yield response to N in STR is that timber residue absorbed manure-N, making it unavailable to the crop. The manure-N bound to timber may not be available to the root system if it remains on the sward surface throughout the growing season. A third possibility is that timber residue may have physically inhibited plant growth either by intercepting light before it reaches the plant or by adding a carbon source to soil and stimulating microbial uptake of soil and manure N. This hypothesis is explored as the third objective of this project.

Objective 3. Determine if land application of timber residue increases soil microbial activity or intercepts light from reaching plants

Objective three aimed to separate the nutrient effect of manure from the physical effect of timber residue by examining the effect of dry timber residue (without manure) on silage DM yield and N response. Results demonstrated that while timber application at rates from 3 to 15 t ha^{-1} had a negative effect on first cut silage DM yield; dry timber residue had no significant effect on silage N uptake. The lack of silage N response to timber indicated timber applied to grassland did not stimulate microbial uptake of soil N. The negative response of first cut silage DM yield indicated timber residue may have a shading effect on the sward which inhibited grass growth for first cut silage. This effect was not observed for the second and third silage cuts. Results from objective one demonstrated that at the time of first cut silage harvest (June 24), average sward coverage of timber decreased less than 3% compared to the timber coverage at the start of the trial (May 23). By second cut harvest (August 10), sward coverage decreased 9% to 14% as timber was incorporated into soil over time. The shading effect from timber residue on the sward surface decreased as timber residue was incorporated into soil over time.

Objective 4. Evaluate effluent from OWPs as a potential N fertiliser source on grassland

Objective four was to evaluate effluent from OWPs as an N source for first and residual cut silage and to compare the crop response to effluent with the response to inorganic N fertiliser and slurry. Site response to N was demonstrated for all trials except Johnstown in 2005 by the significant first cut DM yield response to increasing application of inorganic N fertiliser. These results demonstrated that silage DM yield response to effluent at application rates from 5 to 28 kg N ha^{-1} was significantly greater than crop response to the control treatment for first cut silage. The fertiliser efficiency of effluent (74 to 90%) indicates that effluent N is utilized as efficiently by first cut silage as is inorganic N fertiliser. The comparison of fertiliser and effluent regression lines demonstrated no significant difference between the treatments in all trials for first cut silage DM yield. This result confirms that plant N uptake from effluent treatments was similar to uptake of inorganic N fertiliser in all trials. Approximately 40% of effluent N was in the inorganic form and was available for plant uptake immediately after application. The general lack of residual response among the trials indicates the remaining effluent N mineralized quickly and was utilized by the crop within the first six weeks of growth. Cattle slurry N efficiency was 16 to 50% at a similar N application rate to effluent (27.9 kg N ha^{-1}) for first cut silage DM yield. The lower DM content of effluent compared to slurry, resulted in higher fertiliser efficiency. The high water content of the effluent allowed rapid movement of NH_4-N into soil and less chance of volatilization (Stevens et al., 1992).

The results from this study establish that OWP effluent provides N to for first cut silage when effluent N is applied at rates up to 28 kg ha^{-1}. To prevent scorching, 50 tonnes ha^{-1} is the maximum recommended application rate for farm effluent applied to Irish grassland in summer (Keena, 2002). This application rate would contribute up to 23 kg N · ha^{-1} from the effluent used in this study. Our results indicate 18 to 23 kg ha^{-1} (74 to 90%) of effluent N would be taken up by the plant at the recommended application rate. The advised N fertiliser application for first cut silage is 125 kg ha^{-1} on swards more than four years old (Teagasc, 2004). Therefore, effluent used in this study could contribute 14 to 18% of plant N requirement for first cut silage.

Effluent is effective as a source of nitrogen for Irish grassland. Good agricultural practice stipulates that use of inorganic N fertiliser should therefore be reduced to take account of nitrogen in effluent. However, the N content of agricultural effluents varies due to farms location, production practices, climate and season (Ryan, 1990; Hopkins et al., 1996; Richards, 1999). Effluent samples from six other OWPs throughout Ireland ranged from 97 to 810 mg L^{-1} of total N and contained 25 to 95% plant-available, inorganic N. The ammonium N content ranged from 24 to 424 mg L^{-1} of NH_4-N. Recent investigations of N content of dirty water from dairy farm operations in Ireland (defined based on a biological oxygen value of less than 2500 mg L^{-1} or less than 1% DM) observed similar values of total N ranging from 128 to 987 mg L^{-1} (Martinez-Suller et al., In draft). However, only an average of 13% of total N was in the plant-available ammonium form (NH_4-N). Previous characterization of dirty water from dairy farms throughout Ireland found that effluent contained 20 to 401 mg L^{-1} of total N and 3 to 166 of mg L^{-1} of ammonium (NH_4-N) (Ryan, 1991). Lower ammonium content in the Martinez-Suller et al. (In draft) and Ryan (1991) studies compared to this research may be due to the fact that their samples were taken in late winter when ammonium values are lowest, while this research used effluent collected in spring when ammonium content is higher (Richards, 1999). The high variability between these studies illustrates the variability in the N fertiliser potential of effluent. Because of this high variability, nutrient analysis is recommended prior to application to determine the appropriate application rate.

While the N in OWP effluent stimulates silage DM yield, the applied nutrient loads should be considered due to potential harmful effects on the environment (Paranychianakis et al., 2006). Mismanaged land application of farm effluent can cause degradation of surface and ground waters

(Healy et al., 2004). Much of the intensive dairy farming in Ireland is located on free-draining soils overlying productive aquifers (Daly, 1994). Therefore, there are limits to the volume of effluent that can be spread without incurring the risk of diffuse pollution through the soil system to aquifers or through surface run-off to waterways (Clark et al., 1994). Land application of effluent is associated with a high hydraulic loading, with the potential to not only contribute to environmental degredation through the addition of nutrients, but also augmenting pathways for nutrient transport (Schulte et al., 2006).

Objective 5. Determine the sustainability of land application of OWP materials compared to slurry from conventional livestock housing.

5.1. Livestock materials

Little research has been conducted on the volumes of livestock waste materials generated from OWP systems. To estimate the volume of OWP materials, this study used calculated values based on livestock excretion rates, rainfall and clean timber use. Only one study described how much STR and effluent were generated from an OWP. French and Hickey (2003) calculated an output of 4,859 kg of STR and 5,901 L of effluent per steer over a 151 day winter. Material volumes generated from their research would be equivalent to 656 tonnes of STR and 796 tonnes of effluent applied to silage land at a rate of 27 and 29 tonnes ha^{-1}, respectively, when applied to the simulated dairy farm in the current research. For comparative purposes, these values were reduced by 10% to account for the difference in weight between steers and dairy cows. The current research calculated an STR volume 40% less and an effluent volume 24% less (Table 8) than those produced by French and Hickey (2003).

Previous studies on livestock bedding materials demonstrated approximately 9.0 kg of straw and manure per animal was generated daily from a straw-based livestock housing system (Rom et al., 2001). This straw and manure would be equivalent to 202 tonnes of straw and manure over winter when applied to the simulated dairy farm in the current research. The STR generated from the current research (395 tonnes) is closer to Rom et al.'s (2001) results (202 tonnes) than to French and Hickey's (2003) STR calculations (656 tonnes). The high volume of STR and effluent in the French and Hickey study may be due to the relatively high stocking rate (10 m^2 LU^{-1}) of the OWP and higher rainfall or farm washings contributing to effluent. A high stocking rate would require several dressings of clean timber over the winter; while the stocking rate used in the current research (15 m^2 LU^{-1}) would only require one additional dressing of clean timber over winter.

For the conventional housing scenarios, slurry was applied at a rate of 30 tonnes ha^{-1} (148 kg N · ha^{-1}). This application rate was similar to the recommended slurry application rate for first cut silage (33 tonnes ha^{-1}) (Coulter, 2004). In reality, the effect of dairy parlour washings will increase the volume of slurry generated. However, the N load should not be significantly affected. The N concentration of slurry used in this research was based on the EU Nitrates Directive estimate of N contained in slurry (5.0 kg m^{-3}) (European Communities, 2006). The higher N concentration of slurry compared to STR and effluent combined with the greater volume of slurry produced compared to STR resulted in a 53% greater N load applied from slurry compared to the OWP system. The difference in total N load between the systems had no affect on the results for the maximum silage yield scenario or the 2010 Nitrates Directive scenario because, regardless of the N concentration or volume of STR produced, STR would not contribute N to first cut silage.

The N concentration of OWP effluent varies substantially as demonstrated in chapter four. Lowering the protein content in livestock diet reduces the amount of excretion of N in urine (Delagarde et al., 1997). Annual rainfall between years and locations will also cause the N concentration of effluent to vary. The effluent from the OWP scenario was applied at a rate of 25 tonnes ha^{-1} (10 kg N · ha^{-1}) and the STR was applied at a rate of 16 tonnes ha^{-1} (68 kg N · ha^{-1}). No published data exists on practical application rates for STR or effluent. Farmers may decide to apply these materials to only a portion of silage land. Therefore, it is unknown whether the application rates used in this simulation would be typical for an Irish dairy farm system. However, the application rates of STR and effluent were within the range of the experiments described in chapters three and four and therefore valid calculations could be conducted using N efficiency data from previous research.

5.2. Maximum Silage Yield Scenario

The experiment described in chapter three demonstrated STR does not contribute N to first cut silage irrespective of how much STR is applied. Additional inorganic N fertiliser is necessary to achieve maximum first cut silage yield using OWP housing compared to slurry-based housing. Augustenborg et al. (In Press) demonstrated that increasing rates of timber application to grassland may actually have a negative effect on first cut silage yield. However, this effect has only been demonstrated using clean timber (without manure). Future research should weigh this cost against capital savings, such as lower construction costs of OWPs versus conventional housing. However, other costs from OWPs must also be considered, such as increased costs of labour for OWP maintenance and manure handling.

5.3. 2010 Nitrates Directive Scenario

When inorganic N fertiliser application is restricted, slurry-based systems yield more herbage for first cut silage compared to the OWP system. However, in economic terms the difference in silage yields between these systems is negligible given the currently low cost of silage compared to the high capital-cost of conventional housing systems. Nonetheless, farmers face increasing pressure to reduce production costs in order to maintain competitiveness, and the requirement to purchase additional silage using an OWP system should be considered before replacing conventional housing with OWPs.

For the OWP system, only N from STR was considered to determine the maximum allowable inorganic N fertiliser for the system. The Nitrates Directive does not stipulate that N from agricultural effluent be considered in the farm fertiliser regime. The results described in chapter four demonstrated the N content of effluent is variable and cannot be relied on as an N fertiliser source unless chemical analysis of the effluent indicates N is present in sufficient quantities. Chemical analysis of OWP effluent may not be practical for farmers. Therefore, this research assumed farmers would not consider the N contribution of effluent to silage land and would apply the maximum allowable inorganic N fertiliser.

5.4. System Nitrogen Efficiency

Water quality under and along agricultural land is, among other factors, determined by the discrepancy between N inputs into and outputs from that land (Schroder et al., 2005). Results from this research indicated N efficiency is lower in the OWP system compared to the slurry system. Objective three examined some of the possible reasons why N in STR is not available for crop uptake. The experiment described under objective three demonstrated timber residue (without manure) physically inhibited plant growth for first cut silage by intercepting light before it reached the plant. It was hypothesized that timber residue from OWPs may absorb manure-N, making it unavailable to the crop.

5.5. Housing System Analysis

This study demonstrated that conventional livestock housing required less inorganic N fertiliser for first cut silage (maximum silage yield scenario) and yielded more herbage when fertiliser was restricted (2010 Nitrates Directive scenario) compared to OWP housing. While BAT slurry application resulted in the lowest requirement of inorganic N fertiliser, SP technology also performed better than the OWP system. The SP system reduced inorganic N fertiliser requirements by 54% compared to the OWP system under the maximum silage yield scenario. However, under the 2010 Nitrates Directive scenario there was little difference in inorganic N fertiliser requirements between SP and OWP systems. While the currently used slurry application technology (splash-plate) demonstrated little difference in inorganic N fertiliser requirements compared to OWPs, slurry-based housing has the opportunity to improve N recycling through development of new slurry spreading technologies. If OWPs replace slurry-based housing, best available technologies to improve the nutrient management from OWPs must be developed.

Improving N efficiency of livestock wastes is necessary to maintain production under restricted N fertiliser regimes and to reduce losses to the environment. Improving efficiency of N use is also important from the perspective of lowering costs on farms where incomes are coming under increasing pressure following reforms of the Common Agricultural Policy (Dillon et al., 2003). The results from this study indicate that conversion of dairy housing to OWP facilities would require an increase in fertiliser consumption for first cut silage production under the “maximum silage yield scenario”. This would also conflict with the EU Nitrates Directive requirement to increase N-efficiency. In order to comply with such regulations, technologies which improve N uptake from livestock waste must be implemented. If OWPs are used for livestock housing, new livestock waste management strategies should be investigated to improve the N cycling of this system.

5.6. Model relevance

The model maximized a single objective to determine the impact of land application of OWP materials on inorganic N fertiliser. This research assessed the efficiency of an underlying subsystem (first cut silage) within the dairy farm. Future research on the long term residual effect of STR would improve the model. Previous studies indicate N that is not recovered in the season of application does not provide any benefits to the succeeding crop (Paul and Beauchamp, 1993; Rodrigues et al., 2006; Augustenborg et al., In Review (a); Augustenborg et al., In Review (b)). However, the long-term effect of timber applied to grassland has not been investigated and timber may provide a source of OM that may improve soil condition.

5.7 Implications for policy and practice

The present research contributed to the sustainability of Irish agriculture by examining N recycling from a livestock housing system gaining popularity in the beef and dairy industries. More specifically, the research provided an approximation of the N contribution of waste materials from OWP housing systems to grassland fertilization. Management of livestock waste from OWP housing was analyzed in terms of environmental legislation on N fertiliser use (EU Nitrates Directive) to assist in determining the overall sustainability of the system. While effluent from OWPs was an effective source of N for grassland, integration of STR and effluent data indicated that land application of OWP materials required greater inorganic N fertiliser inputs or resulted in lower silage yields compared to a conventional system. While OWPs improve livestock productivity, this research demonstrated that the current waste management strategy for this system (land application) fails to improve N recycling compared to the conventional system. Ultimately, N that is not recycled in the system will escape to the environment and may negatively impact water resources and the atmosphere (Jarvis et al., 1987; Dosch and Gutser, 1996). Out wintering pads cannot be considered sustainable systems until waste management strategies are developed that minimize the extent of N loss from OWPs to the environment.

Existing cost-benefit analyses of OWPs focus on the capital and production costs associated with these systems (Smith, 2005; French and Boyle, 2007). These costs include construction and maintenance expenses weighed against the financial gain in animal products (milk and meat). The current research identified “hidden” costs associated with OWPs in the form of additional inorganic N fertiliser requirements for silage production or the requirement to purchase additional silage when inorganic N fertiliser use is restricted. The costs associated with waste management from OWPs must be incorporated into future cost-benefit analyses to generate a more complete understanding of this system compared to conventional housing.

The work described in this dissertation was the first research to address the question on whether land application of STR and effluent is an appropriate waste management strategy for OWPs. To date, no other published data exists on waste management from OWPs. The results provide a foundation for future research on long-term sustainability of this system. It is anticipated that government grant aid will be available for construction of OWP systems in Ireland by 2008 (French and Boyle, 2007). The results from this research have implications on the government's financial support of OWPs. In light of the EU Nitrates Directive aim to encourage more efficient use of N from livestock manures, only systems which improve N recycling of manure should receive grant aid. Nitrogen efficiency from OWP systems must improve to meet legislative requirements and guarantee government support. While there are significant implications from the present research, future research is needed before these findings can be translated directly into changes in OWP waste management strategies.

CONCLUSIONS AND RECOMMENDATIONS

Objective 1. Determine whether timber residues decomposed over a growing season when applied to grassland used for silage production

The first objective was achieved through field experiments to determine whether timber residue decomposed over one growing season when applied to grassland used for silage production. The temporal trends in sward cover following applications of timber residues (without manure) were quantified. Results indicated timber residue did not decompose during the growing season but up to one-quarter of timber residue applied to grassland was incorporated into soil.

Objective 2. Evaluate STR from OWPs as a potential N fertiliser for silage production

The second objective evaluated STR from OWPs as a potential N fertiliser for silage production. Nutrient analysis of STR samples indicated the material had sufficient N content to be a potential source of N fertiliser for grassland. Standards set on metal concentration limits of sewage sludge in agriculture did not preclude application of STR to agricultural land (European Communities, 1998). Experiments were conducted to quantify the N uptake of silage from land application of STR. Nitrogen in STR was not available for silage uptake when applied to sward surface at the rates used in this study (40 to 210 kg of N ha^{-1}). The general lack of DM response in either first or residual cut silage indicated N in STR was not taken up by herbage within the four month growing period.

Objective 3. Determine if land application of timber residue increases soil microbial activity or intercepts light from reaching plants

Objective three aimed to separate the nutrient effect of manure from the shading effect of timber by examining the impact of *dry* timber residue (not soiled with manure) on first, second and third cut silage DM yield and N response. A significant negative response was observed for silage DM yield following increasing application of dry timber at rates from 3 to 15 tonnes ha^{-1}, while no significant response was observed in silage N uptake. The lack of silage N response to timber indicated timber applied to grassland did not stimulate microbial uptake of soil N. Timber application had a shading effect on the sward which inhibited grass growth for first cut silage. The shading effect declined as timber residue was incorporated into soil and was not evident twelve weeks after application.

Objective 4. Evaluate effluent from OWPs as a potential N fertiliser source on grassland

Objective four determined whether effluent from OWPs could be utilized as an N fertiliser source on grassland. The nutrient content of OWP effluent was determined for eight OWP systems in Ireland. Plant-available N varied from 24 to 424 NH_4-N L^{-1}. The high variability detected in OWP effluent samples demonstrated the potential variability in N fertiliser potential of effluent. Experiments were conducted to evaluate effluent from OWPs as an N source for first and residual cut silage and to compare the crop response to effluent with the response to inorganic N fertiliser and slurry. The results demonstrated that first cut silage DM yield response to effluent at application rates from 5 to 28 kg N ha^{-1} was significantly greater than crop response to the control treatment where no N was applied. The fertiliser efficiency of effluent (74 to 90%) indicated that effluent N was utilized as efficiently as inorganic N fertiliser for first cut silage yield. Plant N uptake from effluent treatments was similar to uptake of inorganic N fertiliser in all trials. The general lack of residual response among the trials indicated the organic N in effluent mineralized quickly and was utilized by the crop within the first six weeks of growth. The results demonstrated that effluent was effective as a source of N for grassland. Use of inorganic N fertiliser should be reduced to take account for N in effluent.

Objective 5. Determine the sustainability of land application of OWP materials compared to slurry from conventional livestock housing.

The fifth objective of this project aimed to integrate the results from objectives two and four to compare the OWP livestock housing system to a conventional, slurry-based housing system with respect to silage production and optimized N recycling of livestock manure. Results from spent OWP materials were compared to existing data on N recycling from slurry to determine whether moving from conventional cattle housing to OWP systems would improve farm-level N recycling for first cut silage. A static nitrogen cycling model was developed to investigate the land application of livestock materials from an OWP system compared to slurry from conventional livestock housing. The model showed that 80% more inorganic N fertiliser was necessary to achieve maximum spring silage yield using an OWP system compared to a conventional housing system using BAT to apply slurry. Splash-plate technology also performed better than the OWP system. The SP scenario reduced inorganic N fertiliser requirements by 54% compared to the OWP scenario.

PUBLICATIONS FROM THIS PROJECT

SCIENTIFIC JOURNAL PUBLICATIONS

Augustenborg, C.A., O.T. Carton and R.P.O. Schulte (June 2005) Nitrogen recycling from livestock wastes. In R.P.O. Schulte, K. Richards, J. Finn and N. Culleton (Eds.) The Science of Ireland's Rural Environment: Current Research Highlights from Johnstown Castle, Ireland: Teagasc Publication. ISBN: 1 84170 398 2.

O'Driscoll, K., Boyle, L., French, P. and Hanlon A. The effects of out-wintering pad design on dairy cow hoof health and lameness. *Accepted, Journal of Dairy Science, October 2007*

O'Driscoll, K., Boyle, L. and Hanlon, A. A brief note on the validation of a system for recording lying behaviour in dairy cows, Applied Animal Behaviour Science. 2007. *In press*

O'Driscoll, K., von Keyserlingk, M.A.G. and Weary, D.M. 2005. Effects of mixing on drinking and competitive behaviour of dairy calves. Journal of Dairy Science 89:229-233

Submitted scientific publications

Augustenborg, C.A., O.T. Carton, R.P.O. Schulte and I.H. Suffet (In Press) Degradation of forestry timber residue over one growing season following application to grassland in Ireland. Journal of Sustainable Agriculture. Accepted 17 Jan 2007.

O'Driscoll, K., Boyle, L., French, P. and Hanlon A. The effects of design and management of out-wintering pads on the welfare of dairy cows. *Submitted to Acta Agriculturae Scandinavica, Section A, August 2007*

O'Driscoll, K., Boyle, L., French, P., Meaney B. and Hanlon A. The effect of winter housing on cow dirt score, somatic cell score and mastitis incidence in dairy cows *Submitted to Animal, September 2007*

O'Driscoll, K., Boyle, L., French, P. and Hanlon A. The effects of out-wintering pad design on the synchrony of dairy cow behavior. *Submitted to Journal of Dairy Science, October 2007*

O'Driscoll, K., Boyle, L., French, P. and Hanlon A. Winter accommodation affects dairy cow behaviour *Submitted to Applied Animal Behaviour Science, November 2007*

SCIENTIFIC PAPERS IN PREPARATION

O'Driscoll, K., Boyle, L., French, P. and Hanlon A. The effects of out-wintering pad design on dairy cow production, climatic energy demand, and feed intake. *Planned submission to Livestock Science, December 2007*

O'Driscoll, K., Boyle, L., O'Brien. B., Gleeson, D. and Hanlon A. The effect of milking frequency and nutritional level on dairy cow feeding and lying behaviour. *Planned submission to Journal of Dairy Science, November 2007*

REFEREED CONFERENCE PROCEEDINGS

O'Driscoll, K., Boyle, L., French, P. and Hanlon, A. Effect of winter accommodation on dairy cow behavioural synchrony. Proceedings of the 58th Annual Meeting of the European Association for Animal Production, Dublin, Ireland, 26-29 August 2007

Boyle, L., O’Driscoll, K., Olmos, G., Gazzola, P., Gleeson, D and O’Brien, B. Effect of switching milking frequencies on dairy cow welfare. Proceedings of the 58th Annual Meeting of the European Association for Animal Production, Dublin, Ireland, 26-29 August 2007

O’Driscoll, K., Boyle, L., French, P. and Hanlon, A. Changes in feeding and lying behaviour of dairy cows between pasture and winter accommodation. Proceedings of the 41st International Congress of the International society of Applied Ethology, Merida, Mexico, 30 July -3 August, 2007

Boyle, L., O’Driscoll, K., Olmos, G., Gazzola, P., Gleeson, D and O’Brien, B. Effect of switching milking frequencies on dairy cow behaviour, milk leakage and udder firmness. Proceedings of the 41st International congress of the International society of Applied Ethology, Merida, Mexico, 30 July -3 August, 2007

O’Driscoll, K., Boyle, L., French, P. and Hanlon, A. Out-wintering pad design affects woodchip condition. Proceedings of the ADSA/PSA/AMPA/ASAS Joint Annual Meeting, San Antonio, Texas, 8-12 July, 2007 (Animal Science 85:64-65 suppl. 1, 2007).

O’Driscoll, K., Boyle, L., French, P. and Hanlon, A. Effect of out-wintering pad design on cow hoof health. Proceedings of the ADSA/PSA/AMPA/ASAS Joint Annual Meeting, San Antonio, Texas, 8-12 July, 2007 (Animal Science 85:229-229 suppl. 1, 2007)

O’Driscoll, K., Boyle, L., French, P., Meaney, B. and Hanlon, A. Effect of winter housing facilities on animal hygiene, somatic cell score and mastitis incidence. Proceedings of the 13th Congress of the International Society of Animal Hygiene, Tartu, Estonia, 17-21 June 2007

O’Driscoll, K., Boyle, L., French, P. and Hanlon, A. The effects of design of out-wintering pads on dairy cow productivity, feed intake and reproductive performance. Proceedings of the Agricultural Research Forum, Tullamore, Ireland, 12-13 March 2007.

O’Driscoll, K., Boyle, L., O’Brien, B., Gleeson, D. and Hanlon, A. Effect of milking frequency and nutritional level on grazing and lying behaviour of dairy cows. Proceedings of the 40th International congress of the International society of Applied Ethology, Bristol, 8-12 August, 2006.

O’Driscoll, K., Boyle, L., French, P., Meaney, B. and Hanlon, A. Effect of winter housing on cow dirt score, somatic cell score and mastitis incidence in dairy cows. Proceedings of the ADSA/ASAS Joint Annual Meeting, Minneapolis, Minnesota, 9-13 July, 2006. (Animal Science 84:93-93 suppl. 1, 2006)

O’Driscoll, K., Boyle, L., French, P. and Hanlon, A. The effects of design of out-wintering pads on the hoof health and behaviour of dairy cows. Proceedings of the Agricultural Research Forum, Tullamore, Ireland 15-16 March 2006 pp37.

French, P. O’Driscoll, K., Boyle, L and Hanlon, A. Alternative out-wintering pad systems for dairy cows. Proceedings of the Agricultural Research Forum, Tullamore, Ireland, 15-16, March 2006.

O’Driscoll, K., Boyle L., Hanlon, A., O’Brien, B and Gleeson, D. Validation of a system for automatic recording of standing and lying behaviour of dairy cows at pasture. Proceedings of the Agricultural Research Forum, Tullamore, Ireland. 15-16 March 2006.

O’Driscoll, K., Boyle, L., French, P. and Hanlon, A. Winter housing for dairy cows. Proceedings of the 3rd International Workshop on the Assessment of Animal Welfare at Farm and Group Level. Vienna, September 22 – 24, 2005

O'Driscoll, K., M.A.G. von Keyserlingk, and D.M. Weary. 2005. Drinking and competitive behaviour of dairy calves following introduction into a group pen. Advances in Dairy Technology. 17:351

POPULAR PRESS

Boyle, L., Stewart, C., Olmos, G. and O’Driscoll, K. Breeding and building for a happier, more profitable pig. Todays Farm, Vol 18 no.1, January/February 2007 p. 30-31

French, P and O’Driscoll, K. Out-wintering pads for dairy cows. The Irish Farmers Journal, Vol. 58 no. 45, 12 Nov. 05. Section 3 p.4

REFERENCES

Ashworth, S. and Harrison, H. 1983. Evaluation of mulches for use in the home garden. *Horticultural Science*. 18(2): 180-182.

Augustenborg, C. A., Carton, O. T., Schulte, R. P. O. and Suffet, I. H. *In Press*. Degradation of forestry timber residue over one growing season following application to grassland in Ireland. *Journal of Sustainable Agriculture*.

Augustenborg, C. A., Carton, O. T., Schulte, R. P. O. and Suffet, I. H. *In Review (a)*. Dry matter yield and nitrogen uptake response following land application of timber residues from out-wintering pads to first cut silage for Irish grassland. *Communications in Soil Science and Plant Analysis*.

Augustenborg, C. A., Carton, O. T., Schulte, R. P. O. and Suffet, I. H. *In Review (b)*. Silage dry matter yield response to land application of effluent from out-wintering pads to Irish grassland. *Agricultural Water Management*.

Austin, A. T. and Vitousek, P. M. 2000. Precipitation, decomposition and litter decomposability of Metrosideros polymorpha in native forests on Hawaii. *Journal of Ecology*. 88(1): 129-138.

Bartlett, P. C., Miller, G. Y. Lance, S. E. and Heider, L. E. 1992a. Environmental and managerial determinants of somatic cell counts and clininal mastitis incidence in Ohio dairy herds. *Preventive Veterinary Medicine* 14:195-207.

Beachemin, S., N'Dayegamiye, A. and Laverdiere, M. R. 1992. Nitrogen recovery after application of wood wastes to a sandy soil under potato production. *Canadian Journal of Soil Science* 72(2): 89-95.

Blumfield, T. J. and Xu, Z. H. 2003. Impact of harvest residues on soil mineral nitrogen dynamics following clearfall harvesting of a hoop pine plantation in Subtropical Australia. . *Forest Ecology and Management* 179: 55-67.

Borderas, T. F., Pawluczuk, B., dePassille, A. M., & Rushen, J. 2004 Claw hardness of dairy cows: relationship to water content and claw lesions. *Journal of Dairy Science* 87:2085-2093.

Boyle, R. 2005. *Behaviour, welfare, performance and climatic energy demand of yearling dairy heifers on two nutritional levels, out wintered on an all-weather pad or housed indoors in cubicles*. MSc. Thesis, Linkoping, Linkoping.

Bryne, E. 1979. Chemical analysis of agricultural materials. Dublin, An Foras Taluntais.
Central Statistics Office Ireland. 2005, July 26, 2006. Livestock Survey December 2005. from http://www.cso.ie/statistics/livestockdecember.htm.

Chadwick, D. R. and Chen, S. 2002. Manures. 57-83. Eds: P. M. Haygarth and S. C. Jarvis. Agriculture, Hydrology and Water Quality. CAB International.

Chemilab Instruments Ltd. 1985. System 4 Users Manual. Essex, United Kingdom, Chemilab Instruments Ltd.

Clark, J., Lowe, P., Seymour, S. and Ward, N. 1994. Sustainable agriculture and pollution regulation in the UK. Centre for Rural Economy

Clarkson, M. J., Downham, D. Y., Faull, W. B., Hughes, J. W., Manson, F. J., Merritt, J. B., Murray, R. D., Russell, W. B., Sutherst, J. E., & Ward, W. R. 1996. Incidence and prevalence of lameness in dairy cattle. *The Veterinary Record* 138:563-567.

Connor, C.R., Smolker, R. and Bejder, L. 2006. Synchrony, social behaviour and alliance affiliation in Indian Ocean bottlenose dolphins, *Tursiops aduncus. Animal Behaviour* 72:1371-1378

Corns, W. T. and Stockwell, P. B. 1996. The advantages of atomic fluorescence for the measurement of mercury levels in environmental samples. *International Laboratory news*: 2.

Coulter, B. S. 2004. Nutrient and trace element advice for grassland tillage, vegetable and fruit crops. Teagasc: 96.

Daly, D. 1994. Groundwater-quality, pollution and protection - the role of agricultural activities. Dublin, Geological Survey of Ireland, Dublin.

Delagarde, R., Peyraud, J. L. and Delaby, L. 1997. The effect of nitrogen fertililsation level and protein supplementation on herbage intake, feeding behaviour and digestion in grazing dairy cows. *Animal Feed Science Technology*. 66(165-180).

Demirbas, A. 2001. Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Conversion and Management*. 42(11): 1356-1378.

Dillon, P. and Crosse, S. 1997. Current and potential production in a profitable dairying system. 2-33. *Moorepark National Dairy Conference*. Co. Cork, Ireland.

Dillon, P., Horan, B. and Shalloo, L. 2003. Pathways to Increase Profit. 179-210. *National Dairy Conference: Dairying, a new era*, November 12-13. Cork, Ireland.

Donnellan, T., Dillon, P., Shalloo, L., Hennessy, T., and Breen, J. 2002. A Dairy Farming Road Map: Where now for Dairy Farmers? *Proceedings of the Teagasc National Dairy Conference*, Killarney, Ireland.

Donworth, J. "Dear bales of silage." Teagasc Dairy Weekly Farm Management Notes April 1, 2007 http://www.teagasc.ie/newsletters/farmingtips/2006/dairy-20060905.htm.

Dosch, P. and Gutser, R. 1996. Reducing N losses (NH3, N2O, and N2) and immobilization from slurry through optimized application techniques. *Fertiliser Research*. 3: 165-171.

Dumelow, J. and Albutt, R. 1990. *Proceedings of the VIth International Symposium on Diseases of the Ruminant Digit*. British Cattle Veterinary Associationn.130.

Duryea, M. L., English, R. J. and Hermansen, L. A. 1999. A comparison of landscape mulches: chemical, allelopathic, and decomposition properties. *Journal of Arboriculture*. 25(2): 88-98.

Ebina, J., Tsutsui, T. and Shirai, T. 1983. Simultaneous determination of total nitrogen and total phosphorus in water using peroxodisulfate oxidation. *Water Research*. 17: 1721-1726.

Egan, J., Leonard, N., Griffin, J., Hanlon, A., and Poole, D. 2001. A survey of some factors relevant to animal welfare on 249 dairy farms in the Republic of Ireland / data on housing, calving and calf husbandry. *Irish Veterinary Journal,* 54:388-392.

Enevloldsen, C., Grohn, Y. T. and Thysen, I. 1994. Skin injuries on the body and thigh of dairy cows: associations with season, claw health, disease treatment, and other cow characteristics. *Acta Veterinaria Scandinavica*. 35(4): 337-347.

European Communities. 1991. Council Directive of 12 December 1991, concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC). Official Journal of the European Communities. E. Communities: 1-8.

European Communities. 1998. Statutory instruments No. 267 of 1998 (Use of sewage sludge in agriculture). The Stationary Office, Dublin.

European Communities. 2006. Statutory Instrument No. 378 of 2006 (Good Agricultural Practice for Protection of Waters), The Stationary Office Dublin.

Fisher, A. D., Stewart, M., Verkerk, G. A., Morrow, C. J., & Matthews, L. R. 2003 The effects of surface type on lying behaviour and stress responses of dairy cows during periodic weather-induced removal from pasture. *Applied Animal Behaviour Science* 81:1-11.

French, P. and Boyle, L. 2007. Latest results on alternative low cost winter accommodation and crossbreeding studies at Moorepark. Moorepark Dairy Levy Research Update. M. D. P. R. Centre. Fermoy, Ireland, Teagasc, Agriculture and Food Development Authority. 5: 5-13.

French, P. and Hickey, M. C. 2003. Out-wintering pads for cattle - a nutrient budget of animal manure. 121. *Agricultural Research Forum* Tullamore, Ireland

French, P. and Hickey, M. C. 2003. Out-wintering pads; effects on beef cattle production. 121. *AGAPA Conference*.

Gallagher, G. and O'Carroll, J. 2001. Forecast of Roundwood Production from the Forests of Ireland 2001-2015. Dublin, Council on Forestry Research and Development (COFORD).

Gibbons, P., Mulqueen, J. and Rodgers, M. 2006. Eutrophication from Agriculture Sources - Effects of Agriculture Practices on Nitrate Leaching - Soil Investigation. Unpublished ERTDI Final Report. Environmental Protection Agency, Ireland.
http://www.epa.ie/EnvironmentalResearch/Reports/Outputs/

Greenough, P. R. and Vermunt, J. J. 1991. Evaluation of subclinical laminitis in a dairy herd and observations on associated nutritional and management factors. *Veterinary Record* 128:11-17.

Hadas, A., Kautsky, L., Goek, M. and Kara, E. E. 2004. Rates of decomposition of plant residues and available nitrogen in soil, related to residue composition through simulation of carbon and nitrogen turnover. *Soil Biology & Biochemistry*. 36: 255-266.

Hassoun, P. 2002. Cattle feeding behaviour at pasture: a methodology related to on farm measurements. Animal Research. 51:35-41.

Hastie, G. D., Wilson, B., Tufft, L. H. and Thompson, P. M. 2003. Bottlenose dolphins increase breathing synchrony in response to boat traffic. *Marine Mammal Science* 19:74-84.

He, B. J., Zhang, Y., Funk, T. L., Riskowski, G. L. and Y.Yin. 2000. Thermochemical conversion of swine manure: An alternative process for waste treatment and renewable energy production.

Transactions of the American Society of Agricultural and Biological Engineers. 43(6): 1827-1833.

Healy, M. G., Rodgers, M. and Mulqueen, J. 2004. Recirculating sand filters for treatment of synthetic dairy parlor washings. *Journal of Environmental Quality*. 33(713-718).

Hickey, M. C., French, P., and Grant, J. 2002. Out-wintering pads for finishing beef cattle: animal production and welfare. *Animal Science* 75:447-458

Higgins, K. P. and Dodd, A. 1989. A model of the bioclimatic value of shelter to beef cattle. *Journal of Agricultural Engineering Research* 42:149-164.

Hopkins, J., Schnitkey, G. and Tweeten, L. 1996. Impacts of nitrogen control policies on crop and livestock farms at two Ohio farm sites. *Review of Agricultural Economics*. 18: 311-324.

Hoyne, S. and Thomas, A. 2001. Forest residues: Harvesting, storage and fuel values. Belfield, Dublin 4, Ireland, Council on Forestry Research and Development (COFORD).

Hughes, B. O. and Duncan, I. J. 1989. The notion of ethological 'need': Models of motivation and animal welfare. *Animal Behaviour*. 36: 1696-1707.

Humphreys, J., O'Connell, K., Lawless, A. and McNamara, K. 2004. Strategic use of nitrogen in a new environment. Teagasc. Dublin, Ireland.
Humphreys, J., O'Connell, K., Lawless, A., McNamara, K. and Boland, A. 2004. Nutrient Efficiency on Farms. 68-99. *National Dairy Conference: Exploiting the New Era*, 18 November 2004. Co. Cavan, Ireland.

Jarvis, S. C. 1994. The pollution potential and flows of nitrogen to waters and the atmosphere from grassland under grazing. Eds: I. Ap Dewi, R. Axford, I. Fayez, M. Marai and H. Omed. Pollution in Livestock Production. CAB International, Wallingford, United Kingdom.

Jarvis, S. C., Sherwood, M. and Steenvoodren, J. H. A. M. 1987. Nitrogen losses from animal manures: from grazed pastures and from applied slurry. 195-212. Eds: H. G. Van Der Meer, R. J. Unwin, T. A.

Van Dijk and G. C. Ennic. Animal Manure on Grassland and Fodder Crops. Fertiliser or Waste? Martinus Nijhoff Publishers, Dordrecht, The Netherlands.

Keena, C. "Soiled Water." Irish Farmers Journal Nov. 2002: Teagasc. 3 Jan. 2007 <http://www.teagasc.ie/advisory/environment/pressarticles/2002/20021109.htm>.

Kiernan, P. 2004. *Study of the effect of winter housing systems on the welfare of pregnant dairy heifers and first lactation cows.* M.Agr.Sci, University College Dublin, Dublin.

Kossaibati, M. A. and Esslemont, R. J. 1997. The cost of production diseases in dairy herds in England. *The Veterinary Journal*. 154: 41-51.

Labosky, P., Zhang, J. and Royse, D. J. 1991. Ligin biodegradation of nitrogen supplemented red oak (*Quercus rubra*) wood chips with two strains of *Phanerochaete chrysosporium*. *Wood and Fiber Science*. 23(4): 533-542.

Lalande, R., Furlan, V., Angers, D. A. and Lemieux, G. 1998. Soil improvement following addition of chipped wood from twigs. *American Journal of Alternative Agriculture*. 13: 132-137.

Leach, K. A., Logue, D. N., Randall, J. M. and Kempson, S. A. 1998. Claw lesions in dairy cattle: methods for assessment of sole and white line lesions. *The Veterinary Journal* 155:91-102.

Leonard, F. C., O'Connell, J. M. and O'Farrell, K. J. 1996. Effect of overcrowding on claw health in first-calved Friesian heifers. *British Veterinary Journal* 152:459–472.

LeVan-Green, S. L. and Livingston, J. M. 2003. Uses for small-diameter and low-value forest thinnings. *Ecological Restoration*. 21(1): 34-38.

Martin, P. and Bateson, P. 1993. *Measuring Behaviour*. Cambridge, Cambridge university press.

Martinez-Suller, L., Provolo, G., Richards, K., Brennan, D. and Carton, O. T. *In draft*. Estimation of nutrient and hazardous element values on dairy farm dirty water in Co. Wexford (Ireland).

McCormack, S. 2002. Analysis of agricultural materials: Methods used at Johnstown Castle Research Centre, Wexford. Teagasc, Johnstown Castle Research Centre, Wexford, Ireland. 14.

McLaughlin, M. J. and Champion, L. 1987. Sewage sludge as a phosphorous amendment for sesquioxic soils. *Soil Science*. 143(113-119).

Miller, K. and Wood-Gush, D.G.M. 1991. Some effects of housing on the social behaviour of dairy cows. *Animal Production* 53:271–278.

Mitlohner, F. M., Morrow-Tesch, J. L., Wilson, S. C., Dailey, J. W. and McGlone, J. J. 2001. Behavioural sampling techniques for feedlot cattle. *Journal of Animal Science* 79:1189-1193.

Mulbry, W., Kebede-Westhead, E., Pizarro, C. and Sikora, L. 2005. Recycling of manure nutrients: use of algal biomass from dairy manure treatment as a slow release fertiliser. *Bioresource Technology*. 96(4): 451-458.

Nielsen, B. L. 1999. Perceived welfare issues in dairy cattle, with special emphasis on metabolic stress. *Cattle Practice*. 7(1): 97.

O'Callaghan, K., Cripps, P. J., Downham, D. Y. and Murray, R. D. 2003. Subjective and objective assessment of pain and discomfort due to lameness in dairy cattle. *Animal Welfare* 12: 605-610.

O'Connell, A. M., Grove, T. S., Mendham, D. S. and Rance, S. J. 2004. Impact of harvest residue management on soil nitrogen dynamics in Eucalyptus globulus plantations in South Western Australia. *Soil Biology & Biochemistry* 36: 39-48

O'Connell, J., and Meaney, W. J. 1997. Comparison of shredded newspaper and sawdust as bedding for dairy cows: Behavioural, clinical and economic parameters. *Irish Veterinary Journal* 50:167-170.

O'Connell, J., Meaney, W. and Giller, P. S. 1991. An evaluation of four cubicle designs using cattle behaviour criteria. *Irish Veterinary Journal* 44:8-13)

Paranychianakis, N. V., Nikolantonakis, M., Spanakis, Y. and Angelakis, A. N. 2006. The effect of recycled water on the nutrient status of Soultanina grapevines grafted on different rootstocks. *Agricultural Water Management*. 81: 185-198.

Paul, J. W. and Beauchamp, E. G. 1993. Nitrogen availability for corn in soils amended with urea, cattle, slurry, and composted manures. *Canadian Journal of Soil Science*. 73: 253-266.

Peterse, D. J. 1980. *Judgement of bovine claws by the occurrence of sole lesions*. State, Utrecht,The Nertherlands.

Pommel, B. 1995. Value of a heat treated sludge in the phosphorus fertilization. *European Journal of Agronomy*. 4(3): 395-400.

Porter, K. S., Jacobs, J., Lauer, D. A. and Young, R. J. 1975. Nitrogen and phosphorus in the environment. 3-21. Eds: K. S. Porter. Nitrogen and Phosphorus: Food Production, Waste, The Environment. Ann Arbor Science Publishers, Inc, Ann Arbor, Michigan.

Richards, K. 1999. Sources of nitrate leached to groundwater in grassland of Fermoy, Co. Cork. Dublin, Ireland, Trinity College Dublin. Ph.D. thesis: 264.

Rodgers, M., Gibbons, P. and Mulqueen, J. 2003. Nitrate leaching on a sandy loam soil under different dairy wastewater applications. Section 7. 14-19. *I.W.A. Diffuse Pollution Conference*. Dublin, Ireland.

Rodrigues, M. A., Pereira, A., Cabanas, J. E., Dias, L., Pires, J. and Arrobas, M. 2006. Crops use-efficiency of nitrogen from manures permitted in organic farming. *European Journal of Agronomy*. 25: 328-335.

Rom, H. B., Henriksen, K., Dahl, P. and Levring, M. 2001. Quantification of nitrogen losses, and nutrient flow in straw bedded housing systems for cattle. 21. 34-41. *Sustainable handling and utilisation of livestock manure from animals to plants*, 16-19 January 2001. Denmark.

Ryan, M. 1990. Properties of different grades of soiled water and strategies for safe disposal. *Proceedings of Seminar Environmental Impact of Land Spreading of Wastes*, 30-31 May. Teagasc Research Centre, Johnstown Castle, Wexford, Ireland.

Ryan, M. 1991. Safe disposal of farmyard effluent. *Proceedings of Environmental Impact Conference; Management, Treatment and Land-spreading of Manure and Wastes*, September 11-12. Teagasc Research Centre, Johnstown Castle, Wexford, Ireland.

Schroder, J. J., Vertes, F., Chadwick, D. and Sillebak Kristensen, I. 2005. How to compare the nutrient use efficiency of dairy farms. *Dairy Farming Systems and Environment*, 23 Oct. 2005. Maastricht.

Schulte, R. P. O., Richards, K., Daly, K., Kurz, I., McDonald, E. J. and Holden, N. M. 2006. Agriculture, meteorology and water quality in Ireland: A regional evaluation of pressures and pathways of nutrient loss to water. *Biology and Environment*. 106B(2): 117-113.

Sherwood, M. T. 1979. The effects of landspreading of animal manures on water quality. 379-392. Eds: J. K. R. Gasser. Effluents from Livestock. Applied Science Publishers LTD, London.
Shesken, D. J. 2004. *Handbook of Parametric and Nonparametric Statistical Procedures*. Chapman and Hall/CRC, Boca Raton.

Singh, S. S., Ward, W. R., Lautenbach, K. and Murry, R. D. 1993. Behaviour of lame and normal dairy cows in cubicles and in a strawyard. *Veterinary Record*. 133: 204-208.

Smith, K. 2005. Final Report: Survey of Woodchip Corrals and Stand-off Pads in England and Wales; Construction, Operation and Management Practices; and Potential. E. Agency, ADAS UK Limited.

Soumare, M. D., Mnkeni, P. N. S. and Khouma, M. 2002. Effects of Casuarina equisetifolia composted litter and ramial-wood chips on tomato growth and soil properties in Niayes, Senegal. . *Biological Agriculture & Horticulture* 20: 111-123.

Stevens, R. J., Laughlin, R. J. and Frost, J. P. 1992. Effects of separation, dilution, washing and acidification on ammonia volatilization from surface-applied cattle slurry. *Journal of Agricultural Science*. 119(3): 383-389.

Swift, M. J., Heal, O. W. and Anderson, J. M. 1979. *Decomposition in Terrestrial Ecosystems*. Blackwell Scientific Publications, Oxford.

Teagasc. 2004. *Nutrient and Trace Element Advice for Grassland, Tillage, Vegetable and Fruit Crops*. Environmental Research Centre, Johnstown Castle, Wexford, Ireland.

Tiquia, S. M. and Tam, N. F. Y. 2000. Fate of nitrogen during composting of chicken litter. *Environmental Pollution* 110: 535-541.

Van Horn, H. H., Wilkie, A. C., Powers, W. J. and Nordstedt, R. A. 1993. Components of dairy manure management systems. *Journal of Dairy Science*. 77: 2008-2030.

Ward, P. M. L. and Wohlt, J. E. 1996. Use of bedding materials by New Jersey animal industries: Preference and influencing factors [Meeting] *Journal of Dairy Science* 79(Suppl. 1): 234.

Webster, A. J. F. 2002. Effect of housing practices on the development of foot lesions in dairy heifers in early lactation. *Veterinary Record*. 151: 9-12.

Webster, A.J.F. 2001. Effects of housing and two forage diets on the development of claw horn lesions in diary cows at first calving and in first lactation. *The Veterinary Journal* **162**:56-65.

Whitford, W. G., Aldon, E. F., Freckman, D. W., Steinberger, Y. and Parker, L. W. 1989. Effects of organic amendments on soil biota on a degraded rangeland. *Journal of Range Management*. 42(1): 56-60.

Wilkie, A. C. 2000. Reducing dairy manure odor and producing energy. *Biocycle*. 41(9): 48-50.

Willrich, T. L. 1967. Disposal of Animal Wastes In Agriculture and the Quality of our Environment. 415- 428. Eds: N. C. Brady. American Association for the Advancement of Science, Washington, D.C.
Zhang, R. H. and Westerman, P. W. 1997. Solid-liquid separation of animal manure for odor control and nutrient management. *Applied Engineering in Agriculture*. 13(5): 657-664.