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Comparing irrigated biodynamic and conventionally managed dairy farms. 1. Soil and pasture properties

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Abstract. Ten paired irrigated dairy farms under biodynamic (BD) and conventional (CV) management were compared over a 4-year period (1991–94). The paired farms were located in the irrigation districts of northern Victoria and southern New South Wales and were matched for soil type, climate, cattle breed and farm area. Farms had been practising BD principles for an average of 16 years before the commencement of the study and had not received phosphorus (P) fertiliser for an average of 17 years. The effects of farm management on soil chemical and biological properties and the nutritive properties and botanical composition of pasture were examined at varying sampling times during the study.

Soil Olsen extractable P concentrations were consistently 2–3 times higher under CV management at various sampling depths (mean = 22 mg/kg, 0–10 cm), and were generally marginal under BD management in the surface 10 cm (mean = 8.5 mg/kg). Low soil extractable P concentrations were also reflected in consistently lower mean pasture P concentrations under BD management (0.25 compared with 0.35% on CV farms). Lower soil and pasture P concentrations under BD management were the result of a large negative P balance across BD farms (–17 kg P/ha.year). A mean negative P balance under BD management was a result of low P imports (2 kg P/ha.year) in comparison with large quantities of P (19 kg P/ha.year) effectively lost from the farming system through animal products, estimated losses in water runoff and slowly reversible soil P reactions. These results suggest that greater P imports are required to ensure the future sustainability of BD dairy pasture farming systems. There were few differences in soil biological properties, with earthworm weights significantly higher under CV management, but no difference in soil organic carbon, humus concentration, the weight of the organic mat or microbial biomass, between the two management systems.

Introduction

Biodynamic (BD) farming is an alternative form of agriculture, which aims to manage the biological system to avoid the input of synthetic fertilisers, pesticides and herbicides. The philosophy of BD agriculture was developed by Rudolf Steiner (Steiner 1924) and some of the unique characteristics of this form of agriculture are an emphasis on metaphysics and the practice of applying BD preparations. Enhancing soil biological activity is a specific BD objective which is purported to lead to an increased and balanced nutrient availability through soil processes. Biodynamic preparations are made from cow manure, silica, flowers of yarrow, chamomile, dandelion and valerian, oak bark and stinging nettle (Reganold 1995), although the cow manure-based preparation BD 500, is most commonly used in Australian BD agriculture. Like organic agriculture, BD also actively encourages composting and the addition of animal and green manures and deep rooting in plants. However, compost is not commonly applied to BD farms in Australia.

A major objective of alternative forms of agriculture, such as BD, is to improve the social, environmental and economic sustainability of food production systems. However, the sustainability of BD farming systems is not a given, and like other forms of agriculture, sustainability relies on the ability to produce agricultural products of high quality, with profitable returns, while maintaining the natural resource base and having minimal negative effects on the environment and society (Reganold *et al*. 1990). There are several studies which compare measures of economic sustainability (e.g. Koepf 1986; Vereijken 1986; Penfold 1993; Reganold *et al*. 1993) and soil quality (e.g. Pettersson and von Wistinghausen 1979; Forman 1981; Foissner 1987; Penfold 1993; Reganold *et al*. 1993; Penfold *et al*. 1995) under BD and conventional (CV) management. However, many of these studies compared a variety of agricultural industries, used a plot or paddock scale and were conducted in countries outside of Australia. Although an Australian study reported by Forman (1981) compared soil characteristics under farm scale BD and CV management of wheat and pasture, that particular study only investigated differences in one pair of farms. Few studies comprehensively compare BD and CV management, at a farm scale, and none have examined Australian dairy farming systems.

Dairy production is one of Australia's most profitable agricultural industries, with the majority of Australia's milk

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produced in Victoria (Garcia and Fulkerson 2005). Northern Victoria has an advantage over other rain-reliant areas of the state, due to widespread access to water for irrigation in spring, summer and autumn. This irrigation provides a reliable pasture supply and therefore milk production, year round (Garcia and Fulkerson 2005). Despite the growing consumer interest in organic and BD agricultural products (Kinnear 2000), little objective information is available to assess the productivity and sustainability of BD management of irrigated dairy farms. Data comparing milk yields and animal health under BD and CV management are described by Burkitt *et al*. (2007).

The present study examined the effect of BD and CV management on a range of soil chemical and biological properties and pasture characteristics, on 10 paired irrigated dairy farms located in northern Victoria and southern New South Wales (NSW). The main objective of the study was to examine the balance of import and loss of phosphorus (P) under the two farming systems.

Materials and methods

Farm selection and management

Ten flood-irrigated dairy farms representing the population of farms practising BD agriculture in the irrigation districts of northern Victoria and southern NSW were examined in the present study. Conventional farms were selected to provide comparisons with BD farms and farms were matched based on similarity in climate, soil type, cattle breed and farm area. Eighty percent of paired farms were located on the same soil type and 90% of farms in the study shared a common boundary, suggesting that variations in climate and soil types were minimal. Seven paired farms were examined at the beginning of the study (July 1991) and three extra paired farms were included in July 1992, with the study continuing until June 1994. Eight paired farms were examined from the Shepparton and central Goulburn Valley in northern Victoria, one pair from the Torrumbarry region of northern Victoria and one pair from the Wakool district of southern NSW. The farms were situated in zones where the mean annual rainfall was <600 mm (30-year average) and Red Sodosols (Isbell 1996) dominated the sites located in the Shepparton region, while sites in the Torrumbarry and Wakool region included both Red Sodosols and Grey Vertosols (Isbell 1996). All soils examined in the study were predominantly loams and clay loams.

Perennial pastures were sown at least 5 years previously and pastures were intensively grazed by offering small sections of pasture at each grazing and then allowing a period of regrowth. Pastures were composed mainly of perennial ryegrass (*Lolium perenne*), paspalum (*Paspalum dilatatum*) and white clover (*Trifolium repens*). Stocking rates ranged from 1.1–2.6 and 1.2–3.5 cows/ha for BD and CV farms respectively, with mean rates of 2.0 and 2.3 cows/ha. All farms were flood- irrigated and the mean irrigation interval across the 10 paired farms was longer under BD management (15 days) compared with CV management (9 days) ($P < 0.05$), resulting in a slightly lower annual irrigation water use on BD farms (5.5 ML/ha.year) compared with CV farms (6.4 ML/ha.year) but this was not significant. Historically, all farms received regular applications of P, calcium (Ca) and sulfur (S) fertiliser, traditionally in the form of single super phosphate (SSP containing 8.8% P, 22% Ca and 12% S); however, BD farms had not applied synthetic phosphatic fertiliser for an average of 17 years before the commencement of the study. Conventional farms applied mean rates of SSP of 302 kg/ha.year and urea (46% N) at 83 kg/ha.year throughout the study period. Both BD and CV farms applied lime at mean rates of 40 kg/ha.year throughout the duration of the study.

Soil chemical sampling and analyses

One area of ~5 ha within each farm was selected and intensively monitored to maintain homogeneity of soil type, topography and management during the study period. Soil was sampled twice during the study period, to describe differences in soil chemical characteristics between BD and CV management. Approximately 30 soil cores, 3 cm in diameter, were sampled from each farm, from depths of 0–5, 5–10, 0–10, 10–20 cm in October 1991, to investigate the effect of depth on soil nutrient concentrations. The 0–10 cm samples were analysed as this depth conforms to the standard soil testing practice in Victoria for soils under pasture and allowed comparison with published agronomic targets. In a separate sample, the soil organic mat layer was removed from the surface of the 0–5 cm sample and the 'mat' and '0–5 cm (minus mat)' samples were analysed separately.

Soils were subsequently sampled from the 0–10, 10–20 and 20–60 cm depths in March 1993. Thirty soil cores were sampled from each farm from the 0–10 and 10–20 cm depths and 15 cores were sampled per farm from the 20–60 cm subsoil. Soils were sampled from the 20–60 cm layer by pushing a steel tube, 5 cm in diameter into the soil using an electric hammer. The tube containing the soil sample was removed using a chain pulley system. Each soil depth increment, including the organic mat and the 0–5 cm (minus mat) were bulked for each farm and the bulked samples from the organic mat were weighed. All soil samples were dried at 40°C for 48 h, and passed through a 2-mm sieve before analyses.

All soils were analysed for pH (H_2O), electrical conductivity (EC) and chloride (Cl) (1 : 5) (Rayment and Higginson 1992), cation exchange capacity (Gillman and Sumpter 1986), Olsen extractable P (Olsen *et al*. 1954), Skene potassium (K) (Skene 1956), oxidisable organic carbon (OC) with an electrochemical finish (Walkley and Black 1934), total Kjeldahl nitrogen (N) (TKN) (Blakemore *et al*. 1987), EDTA copper (Cu) and zinc (Zn) (Best *et al*. 1985). Total cadmium (Cd) was determined using flame Atomic Absorption Spectroscopy (ASS) following a nitric and perchloric acid digest, while EDTA Cd was determined by extracting soil (1 : 5 soil to solution ratio) with 0.05 mol/L EDTA (pH 6) for 4 h and analysing the filtered supernatant by flame ASS. Soil Cd concentrations were only measured in March 1993. Colwell extractable P (Colwell 1963), total soil P measured using a nitric and perchloric acid digest and humus concentration measured by extraction with sodium hydroxide, freeze drying and then analysing for oxidisable OC (Walkley and Black 1934) and mechanical analysis (Northcote 1979) were measured for soil sampled only in March 1993.

Soil biological sampling and analyses

Soil microbial biomass was measured by taking 20 soil cores (0–10 cm) from five different locations within a selected paddock on six paired farms, 3–4 days after irrigation in March 1993. Samples from each farm were bulked and cooled during transport to the laboratory where they were passed through a 2-mm sieve, while still wet. Sieved soil samples were analysed using both a 10-day fumigation and extraction with 2 mol/L KCl (Amato and Ladd 1988), and a 24-h fumigation procedure followed by extraction with 0.5 mol/L K_2SO_4 (Brookes *et al*. 1985). The Brookes *et al*. (1985) approach uses chloroform to fumigate soil followed by immediate soil extraction to determine C and N concentrations. Extractable C and N concentrations were then compared with that extracted from a non-fumigated soil.

The weight of earthworms was determined by randomly removing 10 soil quadrats (0.1 m^2 and 10 cm deep) from the surface soil layer of a selected paddock within each farm. Samples were taken from nine paired farms in September 1992, before the first irrigation of the season. The soil quadrats were hand sorted within 48 h of sampling to remove earthworms and earthworm cocoons. Adult and juvenile earthworms were stored in 80% ethanol and later identified, counted and weighed wet.

Pasture sampling and analyses

Six perennial pasture samples were taken from two paddocks on each farm, between October 1991 and November 1993. Seven paired farms were sampled in October 1991 and February 1992, nine in May 1992 and 10 paired farms were sampled at the remaining sampling times. At each sampling, ~60 pasture cuts were taken to ground level from each paddock when pastures were between 10 and 20 cm in height (depending on season). A substitute paddock with similar pasture characteristics was sampled when the experimental paddock had recently been grazed or irrigated. Samples were bulked to provide one sample for each farm and a 200-g fresh weight subsample was removed from the bulk sample and then hand separated into perennial ryegrass, white clover, paspalum and weed components (*Rumex* sp., *Cyperus* sp. and *Junecas* sp.) at six different times from October 1991 to August 1993. The different components were dried at 60°C for 72 h and weighed.

A fresh subsample was removed from the bulked pasture sample described above, dried at 60°C for 72 h and ground to pass through a 1-mm sieve. Samples were analysed for total N, nitrate N, P, K, S, sodium (Na), Ca, magnesium (Mg), Cu, Zn, chloride (Cl), manganese (Mn), iron (Fe), selenium (Se) and boron (B) concentrations using inductively coupled plasma optical emission spectroscopy (ICP-OES, Applied Research Laboratories) (Zarcinas and Cartwright 1983). *In vitro* dry matter digestibility (Clarke *et al*. 1982) was determined from bulked pasture samples from five sampling times and the concentration of neutral detergent fibre (NDF) (Georing and van Soest 1970) was determined on four samples.

Phosphorus budget

An average annual P budget was calculated for all farms, based on the amount (kg) of P/ha.year imported and lost from the farms over the 3-year study period. Milk production, purchased feed and animal cull sale data collected from annual farmer surveys and published data (Standing Committee on Agriculture – Ruminants Subcommittee 1990) were used to calculate the concentrations of P imported and lost from farms during the study. The quantity of P effectively lost from the farming system through P sorption reactions was estimated based on the findings of Cayley and Kearney (1999) and Gourley *et al*. (2001). The same soil P sorption loss factors were apportioned to both the BD and CV farms, as definitive data was not available to justify apportioning different P sorption factors. Although BD farms had a significantly lower mean soil extractable P concentration and intuitively may contain less P to be lost to sorption reactions, Barrow *et al*. (1998) and Bolland and Baker (1998) demonstrated that highly fertilised soils sorbed less P, possibly due to the blocking of some sorption sites. The amount of P lost in surface water runoff was estimated based on a review and original research on irrigated CV dairy pasture farms in northern Victoria (Austin 1998). Phosphorus losses in surface runoff under BD management were estimated to be 25% of that measured under CV management based on the findings of Austin (1998) and de Boer (2003). This estimate was also based on findings reported in the present study that the quantity of irrigation water applied was marginally lower and the irrigation frequency and surface soil Olsen P concentrations were significantly lower under BD management (see Table 1).

Table 1. Effects of biodynamic (BD) and conventional (CV) dairy farm management practices on mean extractable P and total P concentrations

Values in bold were log-transformed for statistical analysis; other values are non-transformed. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, n.s., not significant

Soil depth	Olsen P (mg/kg)				Colwell P (mg/kg)				Total P (mg/kg)			
(cm)	BD	CV	s.e.d.	Signif.	BD	CV	s.e.d.	Signif.	BD	CV	s.e.d.	Signif.
					October 1991 (n = 7)							
Mat	36.8	74.1	6.97	*	–	–	–	–	–	–	–	–
0–5	16.3	43.9	3.25	**	–	–	–	–	–	–	–	–
0–5 (minus mat)	13.7	39.3	3.72	**	–	–	–	–	–	–	–	–
0–10	9.0	24.9	2.05	**	–	–	–	–	–	–	–	–
5–10	5.2	14.1	1.24	**	–	–	–	–	–	–	–	–
10–20	2.1	7.5	2.91	n.s.	–	–	–	–	–	–	–	–
					March 1993 (n = 10)							
0–10	8.1	19.6	2.25	***	36.4	87.7	8.53	***	501	640	0.32	**
10–20	**2.6**	**6.3**	0.22	***	**14.2**	**26.1**	0.15	**	279	312	0.16	n.s.
20–60	**1.3**	**3.1**	0.31	*	**8.6**	**13.7**	0.16	*	236	240	0.11	n.s.

Statistical analyses

Analyses were performed using GENSTAT 3. All data were analysed by analysis of variance using a randomised complete block design and differences measured under BD and CV management were considered significant when $P < 0.05$. Data was transformed for soil exchangeable K at a depth of 20–60 cm, exchangeable Ca at 0–10 cm and Olsen and Colwell P concentrations at depths of 10–20 and 20–60 cm because normality assumptions (non-constant variance) for analysis of variance were not met. Where differences between transformed data were significant, raw values are presented in tables, but the transformation is highlighted.

Results

Soil chemical properties

Olsen and Colwell extractable phosphorus and total phosphorus concentrations

Olsen P concentrations were consistently 2–3 times higher ($P < 0.05$) on CV farms compared with BD farms when seven paired farms were sampled in 1991 and 10 paired farms were sampled in 1993 (Table 1). All differences were significant, with the exception of the concentration measured from the 10–20 cm depth in the first sampling period (October 1991). When the surface 0–10 cm of soil was analysed, differences between soil P concentrations using both the Olsen and Colwell extractable P methods were highly significant ($P < 0.001$) when sampled in March 1993, but differences were less significant with increasing soil depth. These elevated Olsen and Colwell P concentrations in the surface soil (0–10 cm) of CV farms were consistent with significantly higher total P concentrations in this second sampling period. In contrast to extractable P concentrations, total P was not significantly different at soil depths greater than 10 cm.

Extractable potassium and nitrogen concentrations

In general there was no farm management effect on soil extractable K and Kjeldahl N concentrations (data not presented). Mean extractable K concentrations were only higher under BD management (327 compared with 216 mg/kg, $P < 0.05$) in the 0–5 cm soil layer analysed in October 1991 and K concentrations were generally within the optimal agronomic range under both farming systems (Gourley 1999). There were no significant differences between soil N concentrations at any of the sampling times and concentrations from the 0–10 cm depth were 0.29 and 0.34% (October 1991) and 0.36 and 0.32% (March 1993) for BD and CV farms, respectively.

Exchangeable cations, pH and electrical conductivity

Farm management had a significant effect on exchangeable Ca and K concentrations; however, these effects were not consistent with depth (Table 2). Conventionally managed farms had higher ($P < 0.05$) exchangeable Ca concentrations when the organic mat layer and soil from the 0–5 and 5–10 cm depths, were analysed in October 1991. The 0–10 cm samples analysed in March 1993, also showed that exchangeable Ca concentrations were higher ($P < 0.05$) under CV management, but this effect was not observed at soil depths >10 cm. In comparison, exchangeable K concentrations were higher ($P < 0.05$) under CV management in the deeper soil layers (10–20 and 20–60 cm) when sampled in March 1993. An exception was the significantly ($P < 0.05$) higher K concentration under BD management when the organic mat layer was sampled in October 1991. Farm management had minimal effect on exchangeable Na and Mg concentrations, with Na concentrations higher ($P < 0.05$) under CV management (soil sampled from 0–5 cm), and Mg concentrations lower ($P < 0.05$) on CV farms (organic mat layer) in October 1991.

Farm management had minimal impact on soil pH values, with only one significant difference measured (data not presented). Soils were more acidic (5.96 compared with 6.33, 0–10 cm, $P < 0.05$) under BD management when sampled in March 1993. In comparison, EC concentrations were lower in the surface 0–5 cm soil (0.17 compared with 0.24 dS/m, $P < 0.05$) and the organic mat layer (0.28 compared with 0.36 dS/m, $P < 0.05$) under BD management when sampled from seven paired farms in October 1991. In March 1993, EC values were also lower ($P < 0.05$) under BD management (0.17 compared with 0.27 dS/m), but only in the 0–10 cm soil depth.

Trace elements

Farm management had no significant effect on the concentration of soil EDTA (available) Cu and Zn sampled at any

Table 2. Effect of biodynamic (BD) and conventional (CV) dairy farm management practices on mean exchangeable cation concentrations measured at different soil depths in October 1991 and March 1993

Values in bold were log-transformed for statistical analysis; other values are non-transformed. Within rows (for each element), means followed by different letters are significantly different at $P = 0.05$

Soil depth (cm)	Exchangeable Na [cmol (+)/kg]			Exchangeable K [cmol (+)/kg]			Exchangeable Ca [cmol (+)/kg]			Exchangeable Mg [cmol (+)/kg]		
	BD	CV	s.e.d.	BD	CV	s.e.d.	BD	CV	s.e.d.	BD	CV	s.e.d.
					October 1991(n = 7)							
Mat	0.43a	0.52a	0.073	1.6a	1.5a	0.13	7.3a	9.0b	0.30	6.6a	5.4b	0.29
0–5 (minus mat)	0.39a	0.49b	0.028	0.96a	0.76b	0.057	4.8a	6.6b	0.52	3.6a	4.0a	0.38
5–10	0.37a	0.45a	0.027	0.49a	0.37a	0.075	4.0a	5.2b	0.35	2.6a	2.7a	0.14
10–20	0.43a	0.50a	0.027	0.45a	0.39a	0.081	4.5a	4.8a	0.28	3.1a	3.0a	0.37
					March 1993(n = 10)							
0–10	0.55a	0.82a	0.166	0.07a	0.09b	0.012	**3.3**a	**3.8**b	0.18	2.6a	3.0a	0.33
10–20	0.54a	0.73a	0.193	0.44a	0.57b	0.056	3.7a	3.8a	0.27	3.3a	3.1a	0.40
20–60	1.4a	1.4a	0.23	**0.47**a	**0.62**b	0.101	5.3a	4.2a	1.34	5.8a	4.7a	1.22

of the soil depths analysed, but results were variable over time (data not presented). Available Cu concentrations in the surface 0–10 cm of soil were 2.3 and 2.2 mg/kg in October 1991 and 4.7 and 4.6 mg/kg in March 1993 under BD and CV management, respectively. Similarly, available Zn concentrations in the surface 10 cm of soil, were 4.6 and 5.2 mg/kg in October 1991 and 8.1 and 7.9 mg/kg in March 1993 on BD and CV farms, respectively. A single analysis of total and EDTA (available) Cd from the 0–10 cm layer of soil in March 1993, showed that farm management had no significant effect on total Cd concentrations, but that surface available Cd concentrations were higher ($P < 0.01$) under CV management, with mean concentrations of 0.21 and 0.29 mg/kg for BD and CV farms, respectively.

Soil organic matter

The weight of the organic mat layer and concentrations of OC and humus did not differ ($P > 0.05$) between BD and CV farming systems (data not presented). Mean soil OC contents for the 0–10 cm sampling depth were 2.62 and 2.57% under BD and CV management, respectively and differences were not significant despite measuring OC at varying depth increments in both October 1991 and March 1993. Similarly, soil humus concentration was not influenced by farm management when analysed from the 0–10, 10–20 or 20–60 cm depths in March 1993.

Soil biological properties

Farm management had no significant effect on the microbial biomass of soil in the surface 10 cm, measured using either method of analysis, but had a significant effect on the total wet weight of earthworms. Mean microbial biomass concentrations were 538 mg/g under BD and 510 mg/g under CV management, with concentrations ranging from 242–989 mg/g and 255–861 mg/g under BD and CV management systems, respectively (data not presented). The total wet weight of earthworms was higher ($P < 0.05$) under CV management, due to the greater weight of *Aporrectodea trapezoides* (purple worm) (Table 3). Purple worm weights were three times greater on CV, compared with BD farms and were the most common species present, along with *Lumbricus rubellus* (red worm). Four other species of common earthworm were also identified in this study including *Aporrectodea caliginosa* (grey worm), *Aporrectodea rosea* (rosy tip worm), *Microscolex dubius* and *Eisenia fetida* (tiger worms).

Pasture properties

Pasture botanical composition

Pasture botanical composition varied little between BD and CV farms, although the percentage of ryegrass was lower under BD than CV management ($P < 0.05$, 40 compared with 50%, s.e.d. = 3.8) in March 1993 (data not presented). The ryegrass component of pasture varied from 40 to 68% under both farming systems and was generally lowest in summer and highest in winter. Mean white clover percentage varied from 20% in spring 1993 to 9% in autumn 1993 under both farming systems. Productive pasture species (ryegrass, white clover and paspalum) consistently made up >85% of the sward under both management approaches.

Pasture nutrient concentrations

Pasture P concentrations were higher ($P < 0.05$) under CV management at every sampling time (Table 4). Mean values ranged from 0.22–0.27% and 0.32–0.36% under BD and CV management, respectively. By contrast, pasture S and N concentrations were significantly higher at only two of the six sampling times under CV management, whereas pasture K concentrations were higher ($P < 0.05$) under BD management at one of the six times (October 1991). Similarly, differences between micronutrients were highly variable over time and the effect of farm management was significant for some nutrients, but only in November 1992. Throughout this sampling period, Cl, Na and Fe concentrations were significantly higher under CV management, whereas Cu ($P < 0.01$) and B ($P < 0.05$) concentrations were significantly lower on CV farms.

Pasture digestibility and neutral detergent fibre

Dry matter digestibility of pastures ranged from 66–71% under BD management and 68–73% on CV farms. Although pasture digestibility was significantly higher under CV management at three out of five sampling times between February 1992 and August 1993, these differences were ≤3%. There was no effect ($P > 0.05$) of farm management on the concentration of NDF, with mean concentrations ranging from 48–58% on BD farms compared with 44–59% on CV farms.

Phosphorus budget

A comparison between the average amount of P imported and effectively lost from 10 paired BD and CV farms, indicates that a large negative P balance (–17 kg P/ha.year) occurred under BD management during this study period (Table 5). The quantity of P effectively lost from CV farms in milk, in animals sold off the property, in surface water runoff and in slowly reversible soil P sorption reactions was ~9 kg P/ha.year higher compared to BD farms. Although similar quantities of P were imported to both farms as supplements, CV farms also imported an average of 27 kg P/ha.year as fertiliser, whereas BD farms imported no P fertiliser. The BD farms examined in the present study regularly applied preparation 500; however, this manure-based preparation is likely to have contributed <0.0002 kg P/ha.year (Parker 1992).

Table 3. Wet weight of earthworms (g/m^2) measured in irrigated dairy pasture soils sampled from paired biodynamic (BD) and conventional (CV) farms in September 1992 ($n = 9$)

*$P < 0.05$; n.s., not significant

Species	BD	CV	s.e.d.	Signif.
L. rubellus	23	18	–	–
A. trapezoides	14	45	–	–
A. caliginosa	12	16	–	–
A. rosea	0.8	3.0	–	–
M. dubius	1.5	0.0	–	–
E. fetida	0.02	0.06	–	–
Total juvenile weight	8	5	3.3	n.s.
Total adult weight	51	82	10.1	*
Total weight	59	87	8.8	*

Table 4. Significant effects of biodynamic (BD) and conventional (CV) dairy farm management on mean macro- and micronutrient concentrations in perennial pastures immediately before grazing

Pastures were measured six times over the study period, but only significant differences are reported here. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

Mineral analysed	Sample date and size	BD	CV	s.e.d.	Signif.
P (%)	Oct. 1991, $n = 7$	0.26	0.34	0.031	*
	Feb. 1992, $n = 7$	0.22	0.32	0.024	**
	May 1992, $n = 9$	0.27	0.36	0.249	**
	Nov. 1992, $n = 10$	0.27	0.36	0.021	**
	Mar. 1993, $n = 10$	0.24	0.33	0.017	***
	Nov. 1993, $n = 10$	0.25	0.36	0.019	***
S (%)	Nov. 1992, $n = 10$	0.24	0.28	0.012	**
	Mar. 1993, $n = 10$	0.31	0.36	0.011	**
Total N (%)	Oct. 1991, $n = 7$	2.10	2.50	0.19	*
	Nov. 1992, $n = 10$	1.70	1.90	0.07	*
Na (%)	Feb. 1992, $n = 7$	0.22	0.40	0.06	*
	May 1992, $n = 9$	0.26	0.48	0.060	**
	Nov. 1992, $n = 10$	0.34	0.45	0.042	*
Cl (%)	Nov. 1992, $n = 10$	2.10	2.70	0.19	*
	Mar. 1993, $n = 10$	1.40	1.30	0.05	*
Ca (%)	Oct. 1991, $n = 7$	0.41	0.49	0.037	*
	Nov. 1993, $n = 10$	0.47	0.54	0.019	*
Cu (mg/kg)	Nov. 1992, $n = 10$	5.50	3.80	0.39	**
B (mg/kg)	Nov. 1992, $n = 10$	11.9	9.70	0.50	*
Fe (mg/kg)	Nov. 1992, $n = 10$	280	360	18.8	*

Discussion

Compared with all other soil or pasture properties examined in the present study, the effects of the farm management system were most evident with the soil Olsen and Colwell extractable P concentrations (Table 1). These differences were driven by the application of SSP at mean rates of 27 kg P/ha.year to CV farms, whereas negligible P was applied under BD management. Although both BD and CV farms had received regular P fertiliser applications in the past, BD farms applied no synthetic P fertiliser for an average of 17 years before the beginning of the study, suggesting that pasture growth, as well as plant P concentrations, may be limited under BD management.

Elevated Olsen P concentrations in the deeper soils layers under CV management (Table 1) suggest that either P is moving down the profile following surface application or that plant roots have adapted under BD management to better access P at depth. Although it is possible that some vertical movement of P may have occurred under flood-irrigation, previous studies on a range of non-irrigated pasture soils have shown minimal movement below a depth of 10 cm (Burkitt *et al*. 2004). Burkitt *et al*. (2004) and research conducted by McCaskill and Cayley (2000) and Ozanne *et al*. (1961), used measures of total P to identify vertical P movement following long-term P fertiliser applications. The present study, however, observed no significant difference between total P concentrations at the 10–20 and 20–60 cm depths between the two management regimes. This suggests that the difference between plant available P concentrations may be due to plants accessing more available P under BD management, rather than from the vertical movement of surface applied P fertiliser under CV management. The likelihood of improved access of limited soil P under BD management is also supported by arbuscular mycorrhizal fungi (AMF) studies published from the same 10 paired BD and CV farms examined in the current study (Ryan

Table 5. The average phosphorus budget for 10 paired biodynamic (BD) and conventionally (CV) irrigated dairy farms located in northern Victoria and southern New South Wales

Data averaged for 3 years between 1990 and 1992. Mean area of BD farms was 62.3 ha compared with 61.7 ha on CV farms

	Biodynamic dairy farm	Conventionally irrigated dairy farm
Imports (kg P/ha.year)		
P fertiliser[A]	0	27.0
Purchased supplements[B]	1.7	3.4
Total imports	1.7	30.4
Losses (kg P/ha.year)		
Milk[C]	6.5	10.1
Animals sold off[D]	2.3	2.5
P lost in surface runoff[E]	1.9	7.5
Soil P sorption[F]	8.0	8.0
Total losses	18.7	28.1
Balance	–17.0	+2.3

[A]CV farms = 302 kg of SSP/ha.year containing 9% P.
[B]BD farms = 38 t DM/year, CV farms = 74 t DM/year containing 2.8 kg P/t (Standing Committee on Agriculture – Ruminants Subcommittee 1990).
[C]BD farms = 402 096 L/year, CV farms = 620 178 L/year containing 0.10% P (Standing Committee on Agriculture – Ruminants Subcommittee 1990).
[D]BD farms = 17 cows and 84 calves/year, CV farms = 18 cows and 99 calves/year containing 8 kg P/t of liveweight (Standing Committee on Agriculture – Ruminants Subcommittee 1990).
[E]Estimate based on de Boer (2003) and Austin (1998).
[F]Estimate based on Gourley *et al*. (2001).

et al. 2000). This published study indicated that percentage colonisation of both grasses and clovers were significantly higher under BD management. The results reported by Ryan *et al*. (2000) concur with those of Dann *et al*. (1996) and Ryan and Ash (1999) who concluded more active AMF colonisation in P limited environments. Furthermore, Ryan *et al*. (2000) reported that the percentage AMF colonisation decreased linearly with increasing soil Olsen P and pasture P concentrations ($P < 0.05$).

Pasture nutrient analysis clearly indicated that plant P concentrations were consistently lower ($P < 0.05$) under BD management compared with CV farms (mean = 0.25 and 0.35% respectively, Table 4) and differences in P fertiliser inputs between the two farming systems are the likely reason. Pinkerton *et al*. (1997) reported that an adequate plant P concentration range required for perennial ryegrass production was 0.25–0.55%, with deficiencies observed at P concentrations <0.13%. However, it is difficult to relate this data to the present study, as on average, ryegrass made up only 54% of the sward in the present study and the published data refers to samples taken from the youngest mature blade, whereas pasture was harvested to ground level in the present study. Despite being unable to prove a pasture P deficiency under BD management, the consistently lower pasture P concentrations are likely to have limited pasture production. A related study comparing the same paired farms examined in the present study, found pasture intake was significantly lower under BD management (Burkitt *et al*. 2007). However, this result could also be influenced by longer irrigation intervals under BD management and differences in grazing management between the two systems, as grazing rotation length and management of pasture residual has been shown to influence pasture growth and intake (Fulkerson and Donaghy 2001). Considering the importance of adequate P nutrition to the production of perennial ryegrass and white clover pastures (Pinkerton *et al*. 1997), the low soil P status measured under BD management, highlights the need to import P into these farms in the short- term, to avoid possible pasture P deficiencies in the future.

Differences in P management were also reflected in the P budget analysis undertaken on the 10 paired farms (Table 5). Although the large negative P balance under BD management contrasts with the range reported (–6.5 to +36 kg P/ha.year) in a review of 56 mostly European organic dairy farm gate budgets (Watson *et al*. 2002), the large negative P balance measured in the present study was primarily due to minimal imports of P into the farming systems, a finding which is consistent with Penfold *et al*. (1995). Lower losses of P in milk and a lower estimate of P losses in water runoff under BD management also contributed to these differences. Phosphorus runoff losses under low P input farming systems are poorly understood and more research is required to accurately estimate these losses in the future. Despite this, large negative P balances under BD management are clearly not sustainable over the longer term and will continue to lower an already marginal plant available Olsen P concentration (8.1 mg/kg, March 1993) in the surface 0–10 cm (Table 1). These findings highlight the need to source organic forms of nutrients containing P, which will maintain farm P balances, while satisfying the requirements of biodynamic certification. This will pose a significant challenge to the industry as one of the fundamental aims of BD management is to achieve a closed agricultural system as far as is practicable (Kirchmann 1994).

The import of P onto BD farms in the form of feed supplements was observed in the present study and the application of reactive phosphate rock (RPR) is allowed under the certification system (Penfold *et al*. 1995). Although the pH of soils examined in the present study are not conducive to optimising the effectiveness of RPR, this fertiliser could be a viable longer term option as the irrigated soil conditions are likely to enhance P dissolution (Sale *et al*. 1997). Despite other Australian organic and biodynamic studies reporting low soil P, grain P concentrations or grain yield under RPR applications (Penfold *et al*. 1995; Dann *et al*. 1996; Ryan *et al*. 2004), these studies were conducted in low rainfall (average annual rainfall of <480mm) non-irrigated environments and it is likely that RPR would be more effective under irrigation. Imports of P in feed supplements and RPR are consistent with the BD aim to maintain and increase soil fertility (Kirchmann 1994), and may provide an opportunity to ensure the sustainability of pasture production in Australia using BD principles. Indeed, a study involving nine organic farms in the UK concluded that positive P balances on six of the farms were due to the application of P as rock phosphate and brought in feed (Berry *et al*. 2003). In contrast to Australian studies, nutrient budgets conducted on a mix of agricultural enterprises by Askegaard and Eriksen (2000) and Berry *et al*. (2003) indicated that K could potentially limit production on organic farms in Denmark and the UK, suggesting that nutrient balances may vary between countries and production systems.

While a positive P balance is acceptable if farm managers are aiming to increase soil P fertility, mean Olsen P concentrations of 19.6 mg/kg (March 1993, 0–10 cm) across the 10 CV farms (Table 1) were optimum for maximising dairy pasture production (Gourley *et al*. 2001). This suggests that future P fertiliser applications should be carefully monitored on these CV farms to balance P losses and to maintain soil P fertility at its current optimum level.

The regular application of mineral fertilisers on CV farms may also explain differences measured with soil exchangeable Ca (Table 2) and available Cd concentration (data not presented). Single super phosphate contains high concentrations of Ca (22%), which, at the average rate of application determined in the present study (302 kg/ha.year), would apply the equivalent of 66 kg Ca/ha.year to CV farms. The current study also suggests that regular SSP application under CV management resulted in significantly higher available Cd concentrations in the surface 10 cm of soil, compared with BD farms. However, concentrations of soil available Cd measured in the present study were all <1 mg/kg, which is below levels of concern for human or animal health (McLaughlin *et al*. 1996). In the past, there has been a widespread concern that the rock phosphate used to make SSP fertilisers in Australia contained high concentrations of Cd (McLaughlin *et al*. 1996), which, if allowed to accumulate in the soil, may pose a risk to human health (Williams and David 1973). However, Australian fertiliser companies have actively sourced low Cd rock phosphates since the mid 1980s (McLaughlin *et al*. 1996) reducing the risk of continued use of SSP under CV management.

Although there were some statistically significant differences in exchangeable K concentrations at varying sampling depths and times (Table 2), more detailed studies are required to verify these differences and to understand the underlying processes. Minimal differences in soil N concentrations may be explained by active N fixation by the white clover component of the pasture sward, which on average, accounted for 16% of the pasture species across BD and CV farms. Shorter irrigation intervals may explain higher salinity (EC) concentrations under CV management in the surface profiles. A more intensive irrigation regime under CV management may exacerbate rising water tables, bringing more saline water to the soil surface; however, salinity concentrations under both management approaches were unlikely to impact on pasture growth (Shaw 1999). In general, differences in nutrient imports in the form of fertilisers and differing irrigation practices are possible explanations for varying soil chemical properties under BD and CV management.

The total wet weight of earthworms present in dairy pasture soils was higher under CV management (Table 3). This finding concurs with Gourley *et al*. (2001) who reported studies comparing earthworm numbers under experimental dairy farmlets which received between 0–140 kg P/ha.year for 6 years. Gourley *et al*. (2001) reported that pasture production increased with increasing P fertiliser applications and they concluded that earthworm numbers were higher under high P regimes due to greater availability of food in the form of decomposing pasture and cattle manure. In contrast to higher weights of earthworms under CV management, there was no difference in soil OC, humus concentrations, the weight of the organic mat or microbial biomass between the two farming systems. This finding differs from that of Reganold *et al*. (1993), who reported that farms managed biodynamically had higher microbial activity and OC contents. However, this study involved a range of agricultural industries including grain, vegetables, dairy and sheep. By comparison, a 6-year, farmlet scale dairy pasture study comparing treatments of no P fertiliser and 140 kg P/ha.year, reported that soil microbiological activity was unaffected by fertiliser treatment (Gourley *et al*. 2001). According to Ryan (1999), this finding is not surprising because enhanced soil microbiological activity relative to CV systems, requires greater imports of organic matter, and soil nutrient concentrations which do not limit agricultural production.

Conclusion

The present study was the first farm scale study to compare soil and pasture properties under BD and CV management in the Australian dairy industry. The results from the present study challenge the perception that BD farm management is more sustainable than CV management. Although a core objective of BD agriculture is to maintain and enhance soil fertility, data from the present study indicate that soil and pasture P concentrations were consistently lower under BD management and an average farm P budget predicts this situation will worsen over time with a –17 kg P/ha.year deficit calculated for BD farms. This result clearly highlights the need to increase P imports into these farming systems with options including the import of organically certified feed supplements, organic P waste products (where available) and RPR fertilisers. Data from the present study also challenged the general perception that BD farm management enhances the soil OC content, microbial activity and presence of earthworms in soil. Results indicate there was no effect of farm management on soil OC and microbial biomass and that earthworm weights, were in fact higher, under CV management. For the first time, the present study has provided an objective comparison between the effect of farm management on soil and on pasture properties and although it has questioned some of the perceptions surrounding the sustainability of BD management, it has also highlighted some of the benefits of BD management such as higher AMF colonisation and minimal difference in soil extractable K and total N concentrations. This is despite no usage of synthetic K or N fertilisers for an average of 17 years before the beginning of the present study.

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References

Amato M, Ladd JN (1988) Assay for microbial biomass based on ninhydrin-reactive nitrogen in extracts of fumigated soils. *Soil Biology & Biochemistry* **20**, 107–114. doi:10.1016/0038-0717(88)90134-4

Askegaard M, Eriksen J (2000) Potassium retention and leaching in an organic crop rotation on loamy sand as affected by contrasting potassium budgets. *Soil Use and Management* **16**, 200–205.

Austin NR (1998) Sustainable use of water and fertiliser in the irrigated dairy industry of Australia. PhD Thesis, University of Melbourne, Melbourne, Australia.

Barrow NJ, Bolland MDA, Allen DG (1998) Effect of previous additions of superphosphate on sorption of phosphate. *Australian Journal of Soil Research* **36**, 359–372. doi:10.1071/S97110

Berry PM, Stockdale EA, Sylvester-Bradley R, Philipps L, Smith KA, Lord EI, Watson CA, Fortune S (2003) N, P and K budgets for crop rotations on nine organic farms in the UK. *Soil Use and Management* **19**, 112–118. doi:10.1079/SUM2003176

Best EK, Manning GK, Grundon NJ (1985) The ability of several soil extractants to identify copper-responsive wheat soils. *Australian Journal of Experimental Agriculture* **25**, 863–868. doi:10.1071/EA9850863

Blakemore LC, Searle PL, Daly BK (1987) Methods for chemical analysis of soils. New Zealand Soil Bureau, Scientific Report No. 10A.

de Boer IJM (2003) Environmental impact assessment of conventional and organic milk production. *Livestock Production Sciences* **80**, 69–77. doi:10.1016/S0301-6226(02)00322-6

Bolland MDA, Baker MJ (1998) Phosphate applied to soil increases the effectiveness of subsequent applications of phosphate for growing wheat shoots. *Australian Journal of Experimental Agriculture* **38**, 865–869. doi:10.1071/EA98079

Brookes PC, Kragt JF, Powlson DS, Jenkinson DS (1985) Chloroform fumigation and the release of soil nitrogen: the effects of fumigation time and temperature. *Soil Biology & Biochemistry* **17**, 831–835. doi:10.1016/0038-0717(85)90143-9

Burkitt LL, Gourley CJP, Sale PWG (2004) Phosphorus auditing cannot account for all of the phosphorus applied to different pasture soils. *Australian Journal of Soil Research* **42**, 89–98. doi:10.1071/SR03025

Burkitt LL, Wales WJ, McDonald JW, Small DR, Jenkin ML (2007) Comparing irrigated biodynamic and conventionally managed dairy farms. 2. Milk production and composition and animal health. *Australian Journal of Experimental Agriculture* **47**, 489–494. doi:10.1071/EA06085

Cayley JWD, Kearney GA (1999) Changes in bicarbonate-extractable phosphorus of a basalt-derived duplex soil associated with applications of superphosphate to pasture grazed by sheep. *Australian Journal of Agricultural Research* **50**, 547–554. doi:10.1071/A98037

Clarke T, Flinn PC, McGowan AA (1982) Low cost pepsin-cellulase assays for prediction of digestibility of herbage. *Grass and Forage Science* **37**, 147–150. doi:10.1111/j.1365-2494.1982.tb01590.x

Colwell JD (1963) The estimation of the phosphorus fertiliser requirements of wheat in southern New South Wales by soil analysis. *Australian Journal of Experimental Agriculture and Animal Husbandry* **6**, 105–120.

Dann PR, Derrick JW, Dumaresq DC, Ryan MH (1996) The response of organic and conventionally grown wheat to superphosphate and reactive phosphate rock. *Australian Journal of Experimental Agriculture* **36**, 71–78. doi:10.1071/EA9960071

Foissner W (1987) The microedaphon in ecofarmed and conventionally farmed dryland cornfields near Vienna (Austria). *Biology and Fertility of Soils* **3**, 45–49. doi:10.1007/BF00260578

Forman T (1981) An introductory study of the bio-dynamic method of agriculture. Diploma Thesis, University of Sydney, Sydney, Australia.

Fulkerson WJ, Donaghy DJ (2001) Plant soluble carbohydrate reserves and senescence – key criteria for developing an effective grazing management system for ryegrass-based pastures: a review. *Australian Journal of Experimental Agriculture* **41**, 261–275. doi:10.1071/EA00062

Garcia SC, Fulkerson WJ (2005) Opportunities for future Australian dairy systems: a review. *Australian Journal of Experimental Agriculture* **45**, 1041–1055. doi:10.1071/EA04143

Georing HK, van Soest PJ (1970) ‘Forage and Fibre Analysis.’ (USDA: Washington DC)

Gillman GP, Sumpter EA (1986) Modification to the compulsive exchange method for measuring exchange characteristics of soils. *Australian Journal of Soil Research* **24**, 61–66. doi:10.1071/SR9860061

Gourley CJP (1999) Potassium. In ‘Soil Analysis: an interpretation manual’. (Eds KI Peverill, LA Sparrow, DJ Reuter) pp. 221–225. (CSIRO Publishing: Melbourne)

Gourley CJP, Ellis M, Awty I (2001) Phosphorus for dairy farms – final report. Department of Natural Resources and Environment, Ellinbank, Vic.

Isbell RF (1996) ‘The Australian soil classification.’ (CSIRO Publishing: Melbourne)

Kinnear S (2000) State of the Australian organic food industry. In ‘Opportunities in organics’. (Ed.V Burnett) pp. 3–7. (Department of Natural Resources and Environment: Rutherglen, Vic.)

Kirchmann H (1994) Biological dynamic farming – an occult form of agriculture. *Journal of Agricultural & Environmental Ethics* **7**, 173–187. doi:10.1007/BF02349036

Koepf HH (1986) Organisation, economic performance and labour requirements on bio-dynamic farms. *Star and Furrow* **66**, 25–37.

McCaskill MR, Cayley JWD (2000) Soil audit of a long-term phosphate experiment in south-western Victoria: total phosphorus, sulfur, nitrogen, and major cations. *Australian Journal of Agricultural Research* **51**, 737–748. doi:10.1071/AR99091

McLaughlin MJ, Tiller KG, Naidu R, Stevens DP (1996) Review: the behaviour and environmental impact of contaminants in fertilisers. *Australian Journal of Soil Research* **34**, 1–54. doi:10.1071/SR9960001

Northcote KH (1979) ‘A factual key of the recognition of Australian soils. Vol. 4.’ (Rellim Technical Publications: Adelaide)

Olsen SR, Cole CV, Watanbe FS, Dean LA (1954) ‘Estimation of available phosphorus in soils by extraction with sodium bicarbonate.’ (U.S. Government Printing Office: Washington DC)

Ozanne PG, Kirton DJ, Shaw TC (1961) The loss of phosphorus from sandy soils. *Australian Journal of Agricultural Research* **12**, 409–423. doi:10.1071/AR9610409

Parker CB (1992) The phosphorus balance of a conventional and a biodynamic dairy farm. Honours Thesis, LaTrobe University, Bundoora, Australia.

Penfold C (1993) Biological farming systems comparative trial – 5 years on. In ‘Biological Farmers of Australia Quarterly Newsletter, December Issue’. pp. 11–13. (Biological Farmers of Australia: Chermside, Qld)

Penfold CM, Miyan MS, Reeves TG, Grierson IT (1995) Biological farming for sustainable agricultural production. *Australian Journal of Experimental Agriculture* **35**, 849–856. doi:10.1071/EA9950849

Pettersson BD, von Wistinghausen E (1979) ‘Effects of organic and inorganic fertilisers on soils and crops, Vol. 1.’ (Woods End Agricultural Institute: Temple, ME)

Pinkerton A, Smith FW, Lewis DC (1997) Pasture species. In ‘Plant analysis: an interpretation manual’. (Eds DJ Reuter, JB Robinson) pp. 285–346. (CSIRO Publishing: Melbourne)

Rayment GE, Higginson FR (1992) ‘Australian laboratory handbook of soil and water chemical methods.’ (Inkata Press: Melbourne)

Reganold JP (1995) Soil quality and profitability of biodynamic and conventional farming systems: a review. *American Journal of Alternative Agriculture* **10**, 36–45.

Reganold JP, Papendick RI, Parr JF (1990) Sustainable agriculture. *Scientific American* **262**, 112–120.

Reganold JP, Palmer AS, Lockhart JC, Macgregor AN (1993) Soil quality and financial performance of biodynamic and conventional farms in New Zealand. *Science* **260**, 344–349. doi:10.1126/science.260.5106.344

Ryan M (1999) Is an enhanced soil biological community, relative to conventional neighbors, a consistent feature of alternative (organic and biodynamic) agricultural systems? *Biological Agriculture and Horticulture* **17**, 131–144.

Ryan M, Ash J (1999) Effects of phosphorus and nitrogen on growth of pasture plants and VAM fungi in SE Australian soils with contrasting fertiliser histories (conventional and biodynamic). *Agriculture Ecosystems & Environment* **73**, 51–62. doi:10.1016/S0167-8809(99)00014-6

Ryan MH, Small DR, Ash JE (2000) Phosphorus controls the level of colonisation by arbuscular mycorrhizal fungi in conventional and biodynamic irrigated dairy pastures. *Australian Journal of Experimental Agriculture* **40**, 663–670. doi:10.1071/EA99005

Ryan MH, Derrick JW, Dann PR (2004) Grain mineral concentrations and yield of wheat grown under organic and conventional management. *Journal of the Science of Food and Agriculture* **84**, 207–216. doi:10.1002/jsfa.1634

Sale PWG, Brown A, Maclaren G, Derbyshire PK, Veitch SM (1997) Pasture environments in Australia where reactive phosphate rock will be an effective phosphate fertiliser. *Australian Journal of Experimental Agriculture* **37**, 1051–1060. doi:10.1071/EA96119

Shaw RJ (1999) Soil salinity-electrical conductivity and chloride In ‘Soil analysis: an interpretation manual’. (Eds KI Peverill, LA Sparrow, DJ Reuter) pp. 129–145. (CSIRO Publishing: Melbourne)

Skene JKM (1956) Soil analysis as an aid to diagnosing deficiencies of phosphorus and potassium. In ‘Proceedings of Australian Plant Nutrition Conference. Melbourne, Australia’. pp. 146–153. (CSIRO: Melbourne)

Steiner R (1924) ‘Agriculture.’ 3rd edn. (Rudolf Steiner Press: London)

Standing Committee on Agriculture – Ruminants Subcommittee (1990) ‘Feeding standards for Australian Livestock: ruminants.’ (CSIRO Publishing: Melbourne)

Vereijken P (1986) From conventional to integrated agriculture. *Netherlands Journal of Agricultural Science* **34**, 387–393.

Walkley A, Black A (1934) An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* **37**, 29–38. doi:10.1097/00010694-193401000-00003

Watson CA, Bengtsson H, Ebbesvik M, Løes AK, Myrbeck A, Salomon E, Schroder J, Stockdale EA (2002) A review of farm-scale nutrient budgets for organic farms as a tool for management of soil fertility. *Soil Use and Management* **18**, 264–273. doi:10.1079/SUM2002127

Williams CH, David DJ (1973) The effect of superphosphate on the cadmium content of soils and plants. *Australian Journal of Soil Research* **11**, 43–56. doi:10.1071/SR9730043

Zarcinas BA, Cartwright B (1983) ‘Analysis of soil and plant material by inductively coupled plasma-optical emission spectrometry. Technical Paper No. 45.’ (CSIRO: Melbourne)

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