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Intensification and diversification of New Zealand agriculture since 1960: An evaluation of current indicators of land use change

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Abstract

Previous studies of New Zealand's environmental and agricultural history have provided a broad-brush characterisation of land use change that potentially misses pivotal fluctuations in land use policy and practice that would inform us of key drivers of ongoing agricultural land use change. Of particular interest to policy makers is the period after the end of agriculture's 'long boom' in the late 1970s, when a dramatic change in economic policy occurred and farming subsidies were removed. A review and principal components analysis of 35 New Zealand agricultural statistics from the past 40 years identified two main patterns of change in land use, production, and farm inputs. One set of variables, which explained 49% of the variation, indicates an overarching, strong and steady trend for agricultural intensification and to a lesser extent diversification, as indicated by (a) increasing stocking rates and yields, (b) increased farm fertiliser, pesticide and food stock inputs, (c) conversion to more intensive forms of agriculture, and (d) diversification into forestry and deer farming. A second group of variables, which explained 22% of overall variation, inflects around 1982/1983, the time of a major shift in agri-economic policy that removed farm subsidies. The second group of changes included some contraction in agriculture (especially in sheep farming) and its associated inputs and a decline in rural population. There is evidence of acceleration in intensification and diversification in the past decade and for slowing in the contraction of the second set of variables between 1997 and 2001. The drivers of these changes are poorly understood and their impacts on biodiversity conservation in farmed landscapes cannot be discerned from the national indicators currently being monitored. The accelerating agricultural intensification over the past 40 years raises concern about whether New Zealand farming is broadly ecologically sustainable now, and especially whether it could remain so in future.

Keywords: Land use change; Intensification; Diversification; Fertilisers

1. Introduction

New Zealand's species-rich lowland ecosystems have been dramatically modified by several significant changes in land use since the arrival of humans (MfE, 1997; Norton and Miller, 2000). Alluvial floodplain forests, fertile wetlands and indigenous grasslands are now largely replaced by agricultural landscapes pre-dominately pastures of introduced grasses and clover *Trifolium* spp. The agricultural sector plays a key role in influencing New Zealand's economy and society, with agricultural-based products currently representing about 53% of merchandise exports (Ballingall and Lattimore, 2004; Statistics New Zealand, 2004).

1.1. A brief history of early New Zealand agriculture

Modification of lowland and montane forests began between 750 and 500 years ago when an increasing Polynesian population used fire to clear the land for agriculture (McGlone, 1989). This was followed by more

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rapid and dramatic modification of the landscape upon the arrival of European settlers in the early 19th century (Aitken, 1944; Molloy, 1980; MfE, 1997; Norton and Miller, 2000). Between 1900 and the mid-1970s, the portion of New Zealand covered by agricultural land and exotic plantations increased from 35% to 60% (Molloy, 1980). Five major phases of agricultural development have been categorised for the period between 1840 and 2002: colonisation, expansion, early intensification, diversification, and later intensification (Molloy, 1980; Langer, 1990; Glasby, 1991; PCE, 2004).

During the colonisation phase (1840–1870), large areas of indigenous grasslands were burnt for grazing and the sheep population increased dramatically (Molloy, 1980; Langer, 1990). These 'unimproved' grasslands were quickly depleted because energy inputs to the system were minimal, and sheep numbers declined. The introduction of refrigerated shipping in 1882 led to an expansion phase driven by rapid removal of indigenous forest and expansion of permanent pasture (Molloy, 1980; Langer, 1990).

The early phase of intensification began around 1920, facilitated by the application of new soil science, fertilisers, and improvements in plant and animal breeding. Between 1920 and 1970, the area of sown pasture remained fairly stable but the number of stocking units increased by about 150% (Molloy, 1980). At the same time, national meat and dairy productivity doubled and wool production tripled (Langer, 1990). However, it is unclear how long this early phase of intensification lasted. Some reports suggest that it ended in the late 1940s (Glasby, 1991; PCE, 2004). Others indicate that the rate of intensification increased after World War II (Molloy, 1980) and continued until as late as 1970 (Molloy, 1980; Langer, 1990).

Similar disparities are reported for the starting date and duration of the next phase of agricultural development, diversification (Molloy, 1980; Langer, 1990; Glasby, 1991; PCE, 2004). There was probably at least some overlap between the early intensification and diversification phases. For example, farmers were able to develop infertile hill country land because the introduction of aerial top dressing in the late 1940s enabled them to fertilise previously inaccessible areas (Molloy, 1980; Langer, 1990). During this phase, the agricultural sector diversified from the traditional sheep and cattle farming to include deer, goats, horticulture and agroforestry.

A later phase of intensification is thought to have started in the 1980s and continued to the present day (PCE, 2004). Certainly, there is evidence of a general trend for more intensive farming systems in the last 10 years (PCE, 2004).

1.2. Aims of this review

The foregoing broad-brush characterisation of New Zealand's environmental and agricultural history potentially misses pivotal fluctuations in land use policy and practice that would inform us of key drivers of ongoing agricultural land use change. In particular, there is a lack of a published synthesis of various agricultural land use and production statistics since the end of agriculture's 'long boom' in the late 1970s. The period is of particular interest to agricultural policy makers because dramatic changes in economic policy, broadly characterised as removal of farming subsidies, were imposed in the early and mid-1980s (Dalziel and Lattimore, 2004). This review attempts a broad-ranging quantitative review of New Zealand agricultural statistics for the 20 years before and after this shock. Our primary aim was to better categorise periods and trends in New Zealand agriculture, but also to consider whether intensification and diversification is accelerating, and how long the agricultural reforms of the 1980s impacted on national-level agricultural statistics.

Over the last few decades in New Zealand, there has been considerable debate about how farming can be conducted to maintain natural capital as well as social well being and economic viability (PCE, 2004). The Ministry of Agriculture and Forestry has, therefore, defined 'sustainable agriculture' as: '*... the use of farming practices which maintain or improve the natural resource base of agriculture, and any parts of the environment influenced by agriculture. Sustainability also requires that agriculture is profitable; that the quality and safety of the food, fibre and other agricultural products are maintained; and that people and communities are able to provide for their social and cultural well-being*.' Our secondary aim was, therefore, to evaluate the utility of the available data and identify gaps in knowledge for future monitoring as part of a more widely ranging review of whether New Zealand is sustainable now and will remain so in future.

Our review complements the recent research of the New Zealand Parliamentary Commissioner for the Environment (PCE, 2004), which examined the environmental sustainability of more intensive farming in New Zealand. The PCE report focused primarily on land use change and collated fragmentary data on management practices within individual sectors mainly during the last decade (Table 1). By searching for national trends in fewer agricultural statistics but over a longer period we sought to put the findings of the PCE into a more historical perspective and assess the agricultural reform impacts. Elsewhere, we will consider potential impacts of agricultural intensification on New Zealand's biodiversity and challenge current conservation priorities in New Zealand.

2. Methods

Annual data for 48 agricultural variables for the period 1960–2002 were derived mainly from the Statistics New Zealand's annual reports on New Zealand Agricultural Statistics and the FAOSTAT database (http://faostat.fao.org/faostat). Appendix A lists the agricultural variables, data sources, and the years that data were available. Changes in the number or type of data presented by Statistics New Zealand in some years meant that some annual estimates

Table 1
Summary of trends in farming practices within sectors in New Zealand that were reported in the PCE report (2004)

Variable	Dairy				Sheep/beef				Deer				Arable			
	Period	Change	%	% p.a.	Period	Change	%	% p.a.	Period	Change	%	% p.a.	Period	Change	%	% p.a.
Scale																
Number of animals	1994–2002	↑	34	0.51	1980–2003	Sheep ↓ Cattle[a] ↓	Sheep 42 Cattle 13	0.16 0.11	1994–2002	↑			1994–2002	↓		
Area (ha)	1994–2002	↑	12	0.35	1981–2002	↓	7	0.09	1994–2002	↑						
Stocking rate	1994–2002	↑	19	0.42	1981–2002	↓										
Number of farms	1994–2002	↓														
Inputs																
Feed supplements		↑														
Synthetic fertilisers	1996–2002	↑	162	1.02	1991–2002	↑	24–28	0.30	1996–2002	↑	244	0.92	1996–2002	↑	110	0.78
Irrigation		↑											1985–2002	↓	43	0.63
Outputs																
Production per ha	1994–2002	↑	34	0.51	1980–2003	↑			1994–2002	Fluctuated[d]						
Production per animal	1994–2002	↑			1980–2003	Sheep[b] ↑ Cattle[c] ↑			1994–2002	Fluctuated[d]						

[a] On intensive sheep/beef farms beef numbers increased over the same period by between 44% and 77%.
[b] Lambing rates have increased by 25% and lamb and mutton carcass weights have increased by 25% and 18%, respectively.
[c] Calving rates have remained stable but beef carcass weights increase by 13%.
[d] Total venison production increased by 38% between 1994 and 2002 but production per hectare and animal was highly variable depending on world prices.

were missing for some variables. For each variable where data were only available for intermittent years, missing values were interpolated from a straight line drawn between years with actual data up to 2002 (Chamberlain et al., 2000). These interpolated data are thereby assumed to represent an index of change rather than absolute values. We have also calculated some new measures from the available statistics to determine indices of stocking rates and production per hectare per year. A crude approximation for overall grazing pressure was calculated using standardised 'stock units' (variable 22) and grazing intensity was quantified using stocking density estimates for the sheep, deer, beef and dairy sectors (variables 23–27).

Principal components analysis (PCA) was used to summarise 35 agricultural variables for each of 40 years (1961–2001; Table 1) and to identify the general gradient of change between years. Multidimensional scaling (Venables and Ripley, 2002) gave nearly identical results to the PCA, so we have simplified interpretation by using the PCA to identify temporal changes and quantify the relative contribution of the agricultural statistics to each of the principal components. To ensure an even weighting of all variables, and to allow the identification of subtle but important factors, data were first standardised (mean = 0; S.D. = 1). All analyses were undertaken using R 2.0.1 (© The R Development Core Team, 2004).

3. Results

3.1. Areas of different land uses

The total area of land classified as occupied for agricultural use in New Zealand is reported very differently by our two main sources of data for this review (Fig. 1a). According to the New Zealand Agricultural Statistics database, the total area of land increased by 20% (0.92% per annum) during the 1960s and 1970s (Fig. 1a), but then declined again over the next 20 years (−1.48% per annum) to such an extent that the occupied area in 2001 was 10% lower than in 1961. However, the rapid step up in area from 1973 to 1975 and step down again in 1987 are clearly artefacts that must indicate different definitions of land use rather than real changes in agriculture. The FAO database shows a much more realistic inter-annual fluctuation, so we used those data for total area in agriculture for our PCA analysis. However, the FAO dataset also has an unrealistic step down in total area of agriculture between 1994 and 1999. Therefore we have interpolated the data for 1994–1999 by joining a straight line between the 1993 and 2000 years for the PCA analysis. Caution is needed when interpreting trends for this indicator on the available data. This illustrates the need for national statistics to use rigorous and consistent definitions of land-use categories so that very long-term comparability of indicators is maintained, and when changes are made, that these are clearly highlighted.

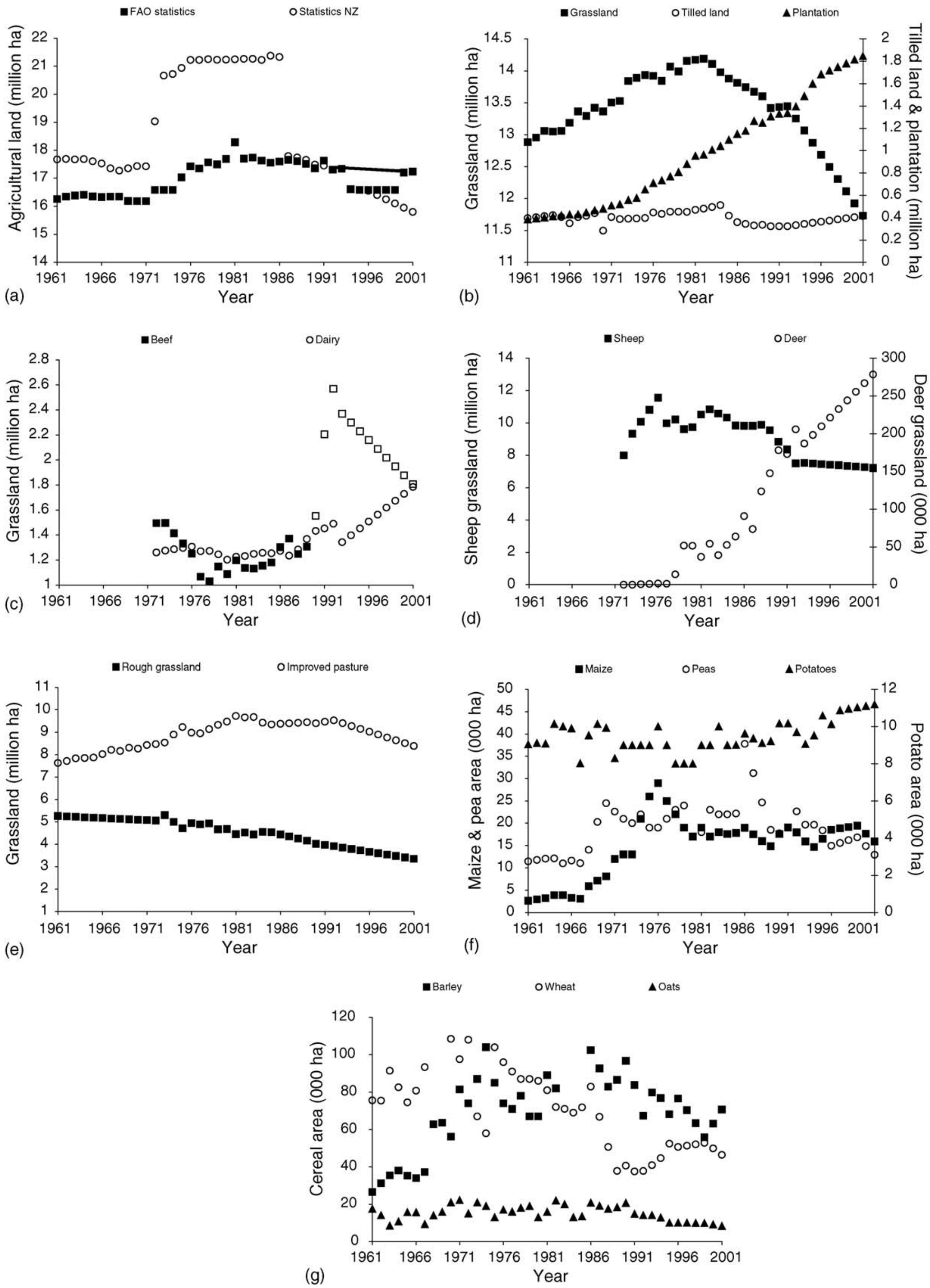

Fig. 1. (a and b) Trends in the total area of land covered by agriculture, grassland, tilled land and plantations (see Appendix A for information on data sources). Note: the interpolated values of total area covered by agriculture (based on the FAOSTAT data series) for the period 1994–1999 are indicated by a line between the relevant points in (a). (c–e) Trends in the total area of grassland covered by each livestock sector and different management practices. The open squares in (c) indicate unreliable data for the grassland estimates for the beef sector, presumably driven by a change in the classification of farm types (Appendix A). (f and g) Trends in the total area of land covered by the main arable crops.

The total area of land dedicated to agriculture in New Zealand was stable in the 1960s, increased steadily in the 1970s, and then levelled off or even slightly declined thereafter (Fig. 1a). There have, however, been significant changes in the area dedicated to different sectors of agriculture since the early 1980s. 'Grassland' remained the dominant land use throughout the study period, but it declined by around 2 million ha in the last 20 years (−0.94% per annum; Fig. 1b). Approximately 0.9 million ha of plantations were added since 1980 (a 110% increase; 3.31% per annum), but even if this new land use had entirely come from grassland, an additional loss of 1.1 million ha of grassland since 1980 remains unaccounted for by the statistics. Creation of grassland reserves has been limited, although 162 of the remaining 305 leasehold properties are currently involved in a tenure review process to promote sustainable use under the Crown Pastoral Land Act 1998 (Mark and McLennan, 2005). Losses to urban expansion may be more important in terms of lost production (because peri-urban areas are often very fertile lowland sites at river mouths) but spread of urban areas will have been relatively slight. The amount of tilled land has remained relatively static since 1980 (Fig. 1b). Small amounts of conversion to viticulture and horticulture have not been incorporated into our analysis. It is possible that the remaining lost grassland since 1980 has mainly reverted to low woody vegetation (MAF, 1996), or that there has been some change in the definition of grassland. These uncertainties could be avoided by tracking changes in both non-production and production habitats in the agricultural landscape. This would enable a more accurate assessment of transfers from one land use to the next, if a full accounting of long-term environmental change is desired.

The records for the areas of grassland for beef rather than dairy/sheep also show some major disjuncts between 1990 and 1993, which must reflect shifts in categorisation when aggregating statistics (Fig. 1c). Similarly the area dedicated to sheep has demonstrated rapid fluxes in 1972–1976 and then in 1988–1990. We could not find any statistics for the split of grassland between the agricultural sectors for the 1960s. Assuming the data in the 1972–1990 period for beef and dairy are comparable, the area of beef farming declined through the 1970s and then regained the area lost in the 1980s while the area of dairy farming increased by 46% (0.71% per annum; Fig. 1c). There has apparently been a general decline in the area of grassland used for sheep since the early 1980s (Fig. 1d) in parallel with the general decline in the total area of New Zealand used for agriculture (Fig. 1a).

Farming of deer was not legal until 1969 but 'after a slow start, increased rapidly from the mid 1970s' (Challies, 1990: p. 456). The area dedicated to deer farming grew fastest in the 1980s and has continued to increase but at a slower rate in the 1990s (Fig. 1d).

A potentially important habitat change for biodiversity throughout the study period has been conversion of 'rough grassland' to 'improved pasture' (Fig. 1e). Conversion from rough grassland, at least those with a high component of native grasses, is likely to be associated with a loss of invertebrate and plant biodiversity (e.g. White, 1991).

Although the area under arable agriculture remained relatively static throughout the four decades (Fig. 1b), there have been major shifts in the types of crops grown. The area of maize *Zea mays* increased steadily in the late 1960s and early 1970s but gradually decreased again in the late 1970s and has remained relatively stable since the early 1980s (Fig. 1f). The area of peas *Pisum* spp. also increased in the late 1960s but then fluctuated from the 1970s onwards, with an overall trend for a decline. Area under cultivation for potatoes *Solanum tuberosum*, New Zealand's staple vegetable, remained relatively stable until the 1990s when it gradually increased. Barley *Hordeum* spp. replaced wheat *Triticum* spp. as the main cereal produced by 1980, but the area of both has declined since (Fig. 1g). Other significant changes in the crop composition, which were not considered in the analyses, include an expansion in the area of vineyards, kiwifruit *Actinidia* spp., and speciality seed crops such as radish *Raphanus sativus*.

The extent and type of changes in land use have also varied between regions. In some regions land use has diversified (e.g. on the Canterbury Plains, where vineyards and speciality seed crops have become more widespread), while other regions have concentrated on major agricultural sectors (e.g. dairy industry in the Waikato region). Rates of conversion to dairy farming have varied between regions, with the dairy herd in Southland increasing by 212% between 1994 and 2002, while the dairy herd only increased by 16% in the Waikato (Statistics New Zealand, 2002). The amount of mature or regenerating native bush in the agricultural landscape also varies greatly between regions (e.g. in 2002 native bush covered 25% of agricultural land in the Waikato versus only 13% in Canterbury; Statistics New Zealand, 2002).

3.2. Animal stocking rates

The national sheep flock increased markedly in the 1960s and 1970s, despite a slight decline in sheep numbers in the early 1970s (Fig. 2a). Over the next 20 years, however, the national sheep flock decreased markedly. By contrast the numbers of dairy cattle increased gradually between 1960 and 1990, and slightly faster since (Fig. 2b). Beef cattle increased until the mid-1970s, declined until the early 1980s, and gradually increased since. Pigs declined rapidly in the 1960s and 1970s, and have continued to decline at a slower rate since (Fig. 2a).

Official counts of the national farmed deer herd start in 1979 when 42,080 were farmed (Table 1). We have therefore assumed zero farmed deer from 1961 until 1974 and interpolated the increase from zero to 42,080 in 1979 (Fig. 2a) for the PCA.

The total national stock units climbed sharply through the 1960s, levelled in the early 1970s, increased further in the late 1970s, and then declined by around 15% in the last two decades (−0.83% per annum; Fig. 2c). This latter decline is driven mainly by reduction in the number of sheep.

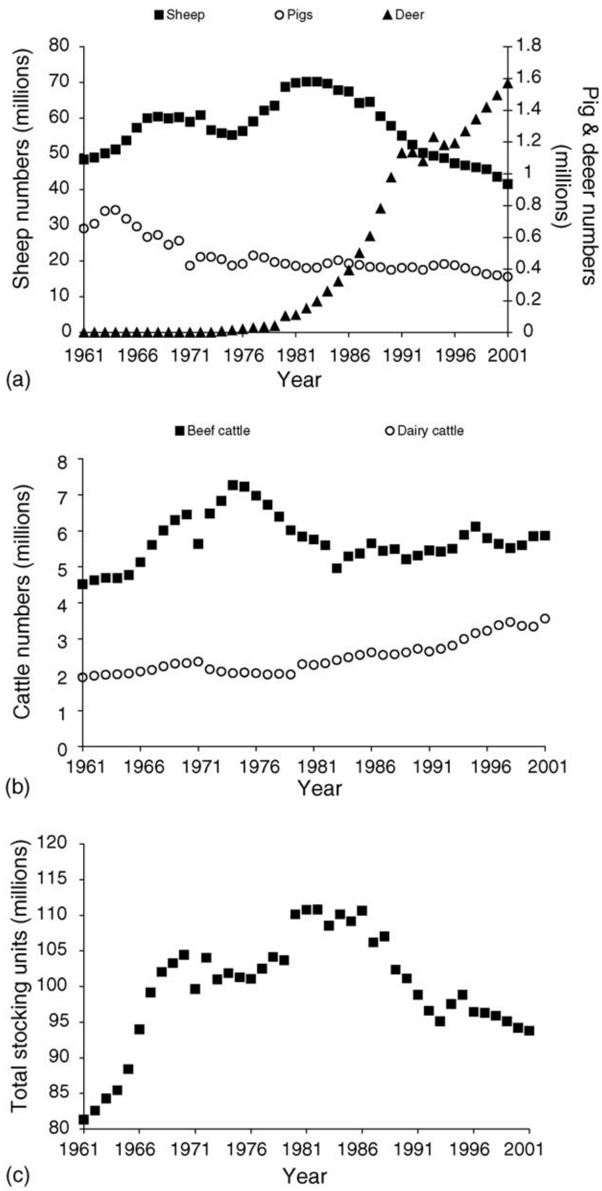

Fig. 2. (a–c) Trends in livestock composition (presented as the total number of animals in each sector and the total number of stocking units; see Appendix A for definitions).

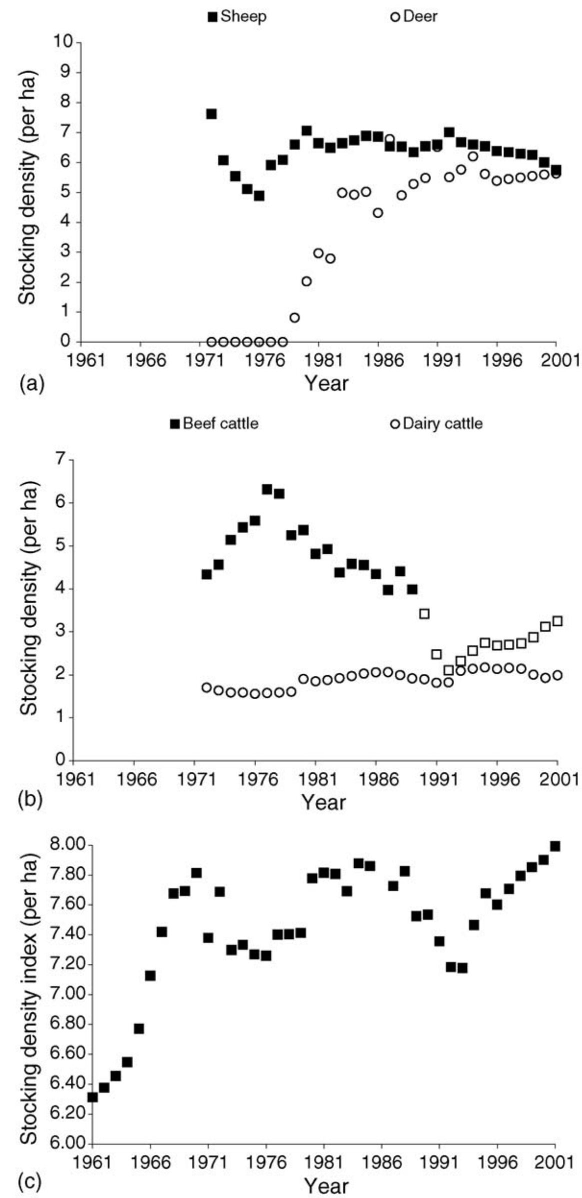

Fig. 3. (a–c) Trends in stocking density. The open squares in (b) indicate unreliable data for the grassland estimates for the beef sector, presumably driven by a change in the classification of farm types (Appendix A).

Our analysis has ignored goats, horses and a variety of new grazers (e.g. alpaca *Lama pacos*, llamas *L. glama*) as having numbers too low to influence dominant trends in agriculture. Similarly, we have ignored grazing by pigs because they are relatively low in numbers and are often fed supplements.

One index of the intensity of agricultural livestock production is the stocking rate (heads per unit grassland area; Fig. 3a–c). Unfortunately, estimating per hectare flock, herd and stock unit data for each sector is extremely difficult to achieve from the published records because there are no consistently reported measures of the area of pastoral land used for dairy, dry beef stock, or sheep and even the total area under pastoral land use shows inflections that are likely to represent inconsistent land-use categorisation (see discussion above for Fig. 1c and d). Also, the science of classifying stock units is not always accurate (Woodford and Nicol, 2005). For example, the size and productivity of stock have changed over time and farming systems have diversified.

Our best interpretation is that beef stocking rates climbed in the 1970s, but then declined steadily through the 1980s (Fig. 3b). The disjunct in area in beef farming between 1990 and 1993 (Fig. 1c) makes us very sceptical of the apparent ongoing decline in sheep/beef stocking rates in the last 10 years (Fig. 3b). The dairy-stocking rate has exhibited a very slight rise throughout the 30-year period (0.54% per annum). Sheep stocking rates have probably stayed reasonably static (Fig. 3a), at least within the bounds of inference associated with uncertainty of measurement of the area under sheep/ beef farming (Fig. 1d).

Deer stocking rates rose dramatically through the late 1970s as more farmers established deer farms and the national domestic herd was built up, but it then stabilised from the early to mid-1980s (Fig. 3a).

The lack of differentiated sector data for the 1960s and uncertainties in the way areas have been measured later force us to use the somewhat crude 'stock unit' measures for all grazers (Fig. 2c). We divided this index by the total area of grassland to estimate total average grazing pressure on grassland (Fig. 3c). The index shows a 24% increase in the 1960s (2.5% per annum), and then dips in the mid-1970s and late 1980s amidst a generally high stocking rate over the past three decades. We used this aggregated index of pastoral stocking rates in the PCA to avoid the inconsistencies emphasised in the stocking rate measures for individual pastoral sectors as described above.

3.3. Changing yield

One way of quantifying yield is to express the production of wool, meat, and milk per year per head of stock. In the past 40 years, beef and veal yields measured in this way increased by approximately 68% (1.29% per annum; Fig. 4a) and bovine milk yields by about 30% (0.78% per annum; Fig. 4a). In contrast there was very little change in the wool clip per head, and only a slight decline in mutton and lamb yields from 1961 to 1986, followed by a steady increase to reach 5% higher per capita yield in 2001 compared with 1961 (Fig. 4b). Another measure of productivity per head of stock is lambing and calving rates. Although lambing rates declined by about 1.2% per annum between 1966 and 1973, they recovered in the late 1970s and returned to similar rates to those observed in the early 1960s (Fig. 4c). Lambing rates then remained relatively stable until 1991, but have since increased at a rate of 1.7% per

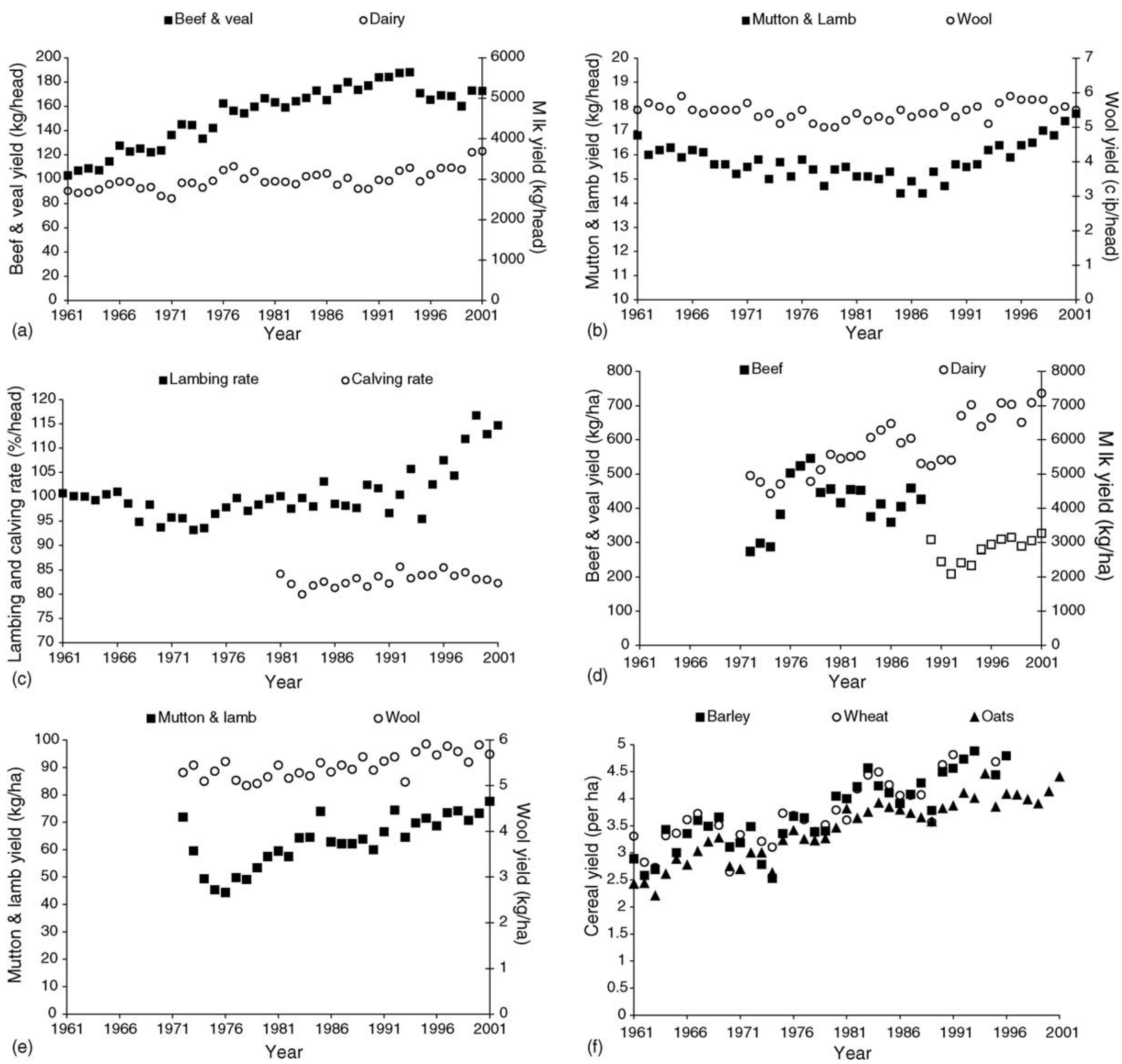

Fig. 4. (a–c) Trends in meat, milk, wool, lambing and calving yields per animal per animal. (d–f) Yields per hectare for livestock (meat, milk and wool) and cereal crops. The open squares in (d) indicate unreliable data for the grassland estimates for the beef sector, presumably driven by a change in the classification of farm types (Appendix A).

annum. In contrast, calving rates remained fairly stable between 1981 and 2001 (Fig. 4c).

The most useful measure of intensity of agriculture is to measure yields based on a quantity of produce extracted per unit area of land per year. We have calculated these for the pastoral sectors by multiplying stocking rates (Fig. 3) by per capita annual production (Fig. 4a–c). Yield probably declined for beef meat through the 1980s, but again we warn that changes in the way area in beef farming was estimated could have introduced errors (Fig. 4d). In contrast, annual milk production per hectare has risen at an annual rate of 1.4% since the early 1970s (Fig. 4d). There has been a 2.1% and 0.3% per annum growth in mutton and lamb and wool yield per hectare, respectively, since 1975 (Fig. 4e).

Yields per hectare of barley, oats *Avena* and wheat have each nearly doubled between 1961 and 2001 (Fig. 4f).

3.4. Farm inputs

Increasing yields in the cropping and livestock industry in New Zealand were associated with a twofold overall increase in non-nitrogenous fertiliser input from 1961 to 2001, although with a dramatic drop from 1983 until the end of the 1980s (Fig. 5a). There was a 60-fold increase in nitrogenous fertiliser application over the same period, albeit from a very low initial level (Fig. 5a). Use of both nitrogenous and non-nitrogenous fertilisers has increased rapidly since 1990.

There are insufficient data to investigate temporal trends in pesticide use. However, the total amount of liquid pesticides (which included herbicides, insecticides and fungicides) that was aerially sprayed on farms quadrupled between 1960 and 1985 (Statistics New Zealand) and pesticide consumption is estimated to have tripled between 1993 and 2001 (measured as tonnes of active ingredient; J. Richardson, Agcarm, personal communication). This suggests that pesticide use has increased by at least an order of magnitude in New Zealand over the past four decades. In 1998, pesticide use was dominated by herbicides (68%), followed by fungicides (24%) and insecticides (8%), but patterns of pesticide use varied both between and within sectors of the agricultural industry (Holland and Rahman, 1999). Dairy farming used seven times more herbicide per hectare than sheep and beef farming (i.e. 0.28 kg active ingredient ha^{-1} yr^{-1} versus 0.04 kg active ingredient ha^{-1} yr^{-1}). Within arable farming, herbicide use ranged from 0.7 kg ha^{-1} yr^{-1} for legume seed crops to 4.5 kg ha^{-1} yr^{-1} for maize crops.

When shortage of feed threatens production, the majority of pastoral farmers (especially dairy farmers) have traditionally relied on off-farm grazing of grass, off-farm import of silage, some crops in winter (especially *Brassica* spp.), and maize silage in areas where it can be grown. However, there is a rapidly increasing trend to buy in stock feeds from overseas to carry the herd through seasonal or unseasonable periods when drought or low-temperature periods have reduced pasture growth (Fig. 5b). Ingredients are purchased overseas to combine in New Zealand, including bran and pollard

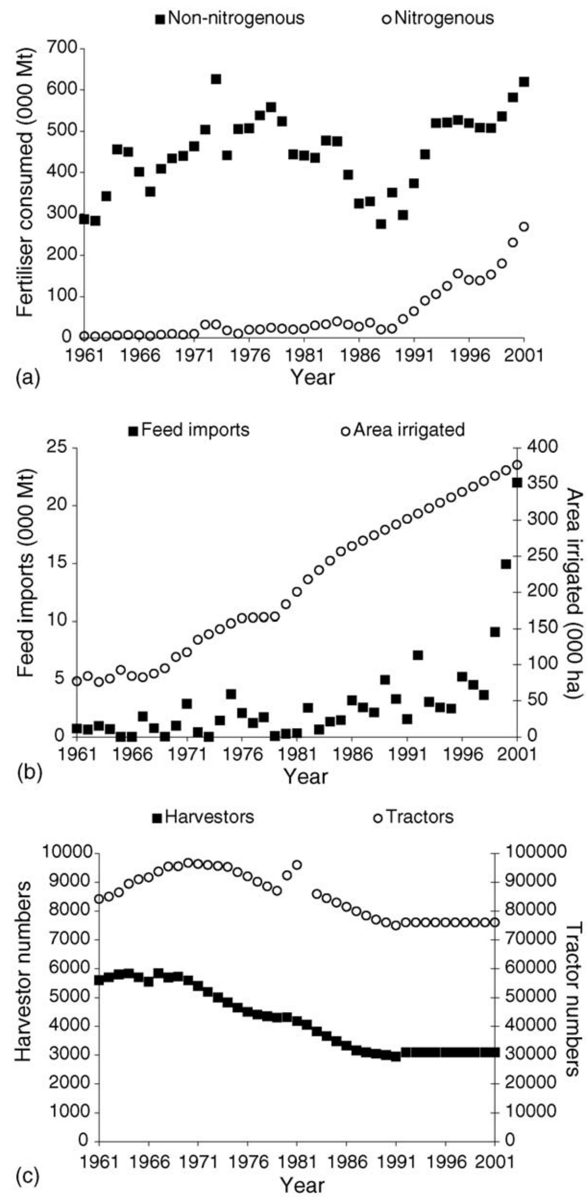

Fig. 5. Trends in fertiliser, imported supplementary animal feed, water and machinery inputs (Mt = metric tonnes).

(predominantly seed germ and skin after extraction of flour), cottonseed *Gossypium* spp., palm *Elaeis* spp. kernel extract and linseed *Linum usitatissimum*.

Input of water from irrigation schemes is the key to intensification of land use in drought-prone regions or where a seasonal low in rainfall regularly constrains stock carrying capacity. The area of land under irrigation increased by 400% over the last four decades (4.0% per annum) but, in 2001, still only covered 2% of the total area occupied by agriculture (Fig. 5b).

Increasing yields have also been associated with a trend towards mechanisation of farming practices (Olson and Holland, 1995). However, the number of tractors and harvestors in use declined through the 1970s and 1980s (Fig. 5c). The decrease in the area of land occupied by agriculture may partly have driven these declines, but the development of larger, more powerful and efficient machinery has reduced the number of machines required for farming. Also as machinery has become more advanced and specialised, farmers have tended to use specialist contractors rather than purchase machinery (Jon Manhire, The Agribusiness Group, personal communication).

Energy inputs are another important resource influencing farming productivity. Direct farm energy inputs are those used in on-farm activities, such as fuel and electricity. Indirect inputs are the energy requirements to manufacture and transport consumables such as fertiliser, agrochemicals, supplementary bought-in feed, seed, and products for farm maintenance, as well as the production costs associated with leased pasture. Capital inputs are the energy requirements for the manufacture of capital items such as vehicles, machinery, and other farm improvements. We were unable to find long-term data on energy use on New Zealand farms. However, overall energy use has probably increased substantially over the last four decades because the use of fertilisers, supplementary bought-in feed, and irrigation has increased significantly. Indeed, energy use on 'average' dairy farms alone doubled between 1977 and the late 1990s (Wells, 2001). Direct energy inputs in the dairy sector increased by about 30% between 1992 and 2002 (PCE, 2004). Energy use in the dairy sector varies between regions and is particularly high in the Canterbury region where irrigated farms have high levels of energy input, associated mainly with pumped irrigation but also higher fertiliser application rates (Wells, 2001).

3.5. Agricultural population and land prices

A sharp decline in agricultural population in the 1960s (Fig. 6) probably represents urban drift because there was a trend at that time for an increase in farm sizes and probably also a decline in rural employment opportunities over the same period (Fairweather, 1985). However, there was a sharp repopulation of rural areas in the 1970s probably driven by an increase in horticulture and small holdings (Fig. 6; Gouin et al., 1994). Depopulation in the 1990s coincides with a rapid increase in the price of rural land (Fig. 6), but we caution that this change in statistics may be an artefact of changes in the way that the agricultural population size was estimated during this period (J. Fairweather, Lincoln University, personal communication).

3.6. Principal components analysis

The temporal change in agricultural practices for the 40-year study period was well summarised by two axes using principal components analysis (Table 2; proportion of variance described = 0.71). Adding a third principal component increased the proportion of variance described to 0.79. This gain is modest when the proportion of variance described is already so high (Manly, 2005), so we retained the two-dimensional ordination.

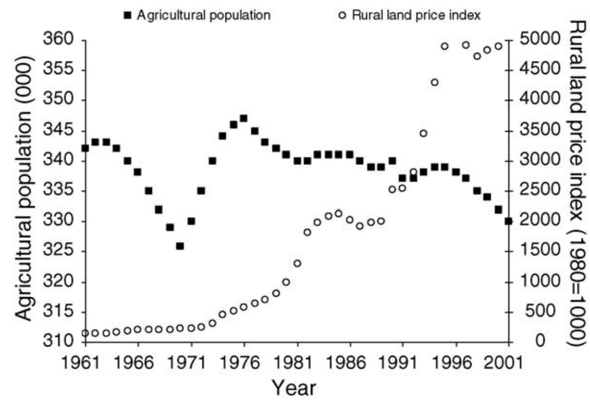

Fig. 6. Trends in the agricultural population and land price index.

The scores for the primary axis demonstrated a positive relationship with year, while trends in scores in the second axis rose to a broad plateau in the early 1980s before declining again (Fig. 7). When the two PCA scores are plotted against one another, 1982 and 1983 is identified as an inflection point (Fig. 8). These two axes therefore identify two distinct patterns and periods of temporal change in agricultural practices within New Zealand over the past 40 years.

The size and sign of the coefficients of the agricultural variables indicate their relative contribution to each of the two principal components (Table 2). The first principal component, which captured most of the variation (49%), is mainly associated with strong positive influences of (a) the advent of new industries (forestry, deer) and (b) increasing numbers of dairy cows, (c) increasing yields (wheat, barley, oats and to a lesser extent, beef, milk and lambing rates), (d) increased farm inputs (fertiliser, water and animal feed) and (e) rising land prices. There are also strong negative relationships with (f) the area of rough pasture and numbers of (g) pigs, (h) tractors and (i) harvesters. These results suggest that annual scores in the first principal component are mainly indicative of agricultural intensification and land development and to a lesser extent with diversification into new industries.

The coefficients for the second principal component (Table 2), which explains 22% of the variance, are strongly positively influenced by (a) the areas used for growing (total agricultural, improved pasture, cereals and grains), (b) the number of sheep and total stock units (which itself is mainly influenced by sheep numbers) and (c) stocking units per hectare. There are strong negative relationships between the second principal component and (d) mutton and lamb meat yield, (e) lambing yield and (f) wool yield, (g) input rates of non-nitrogenous fertiliser, and to a lesser extent, (h) nitrogenous fertiliser applications, (i) animal feed imports and (j) the area planted in potatoes. Collectively, the second principal component codes mainly for the extent and stocking rate of the sheep industry, together with levels of fertilisation and food inputs to the agroecosystem.

Trend in the main intensification and diversification index (PC1) shows a distinct increase in slope after 1982/1983 (Fig. 7a). Fitting a linear model to the trend explains 95.8%

Table 2
Coefficients for the 35 variables included in the PCA analysis

Agricultural feature	Variable no.	Variable	Units measured	PC1	PC2
Land use area	1	Total land occupied (FAO)	Area	0.146	0.230
	3	Tilled land	Area	−0.059	0.081
	4	Plantations	Area	0.239	0.013
	6	Deer grassland	Area	0.233	−0.053
	9	Rough pasture	Area	−0.238	0.003
	10	Improved pasture	Area	0.112	0.296
	11	Maize	Area	0.127	0.231
	12	Peas	Area	0.020	0.282
	13	Potatoes	Area	0.147	−0.166
	14	Barley	Area	0.068	0.278
	15	Wheat	Area	−0.178	0.024
	16	Oats	Area	−0.099	0.278
Stock composition	17	Sheep	Numbers	−0.096	0.293
	18	Deer	Numbers	0.230	−0.079
	19	Beef cattle	Numbers	0.000	0.148
	20	Dairy cattle	Numbers	0.227	−0.065
	21	Pigs	Numbers	−0.181	−0.197
	22	Stock units	Units	0.021	0.329
Stocking density	27	Stock units	Units ha^{-1}	0.134	0.193
Yield per animal	29	Beef and veal	kg $head^{-1}$	0.195	0.183
	28	Cows milk	kg $head^{-1}$	0.181	−0.001
	30	Mutton and lamb	kg $head^{-1}$	0.095	−0.287
	31	Wool (greasy)	Greasy kg clip $head^{-1}$	0.055	−0.227
	36	Lambing rate	% $head^{-1}$	0.174	−0.157
	38	Barley	tonnes ha^{-1}	0.222	−0.040
	39	Wheat	tonnes ha^{-1}	0.229	−0.041
	40	Oats	tonnes ha^{-1}	0.218	0.101
Agricultural inputs	41	Non-nitrogenous fertiliser	tonnes	0.092	0.000
	42	Nitrogenous fertiliser	tonnes	0.217	−0.113
	43	Animal feed imports	tonnes	0.172	−0.102
	44	Irrigation	Area	0.236	0.047
	45	Harvester	Numbers	−0.218	−0.117
	46	Tractors	Numbers	−0.193	0.073
Other indicators	47	Agricultural population	Numbers	−0.057	0.110
	48	Land price	Index	0.234	−0.044

The scores indicate the relative contribution to each of the first two principal components (PC1 and PC2).

of the variance, whereas, a second order polynomial explains 99.1%. This suggests that the rate of intensification of New Zealand agriculture has itself increased in the past 20 years. This increase in the rate of intensification appears to be driven primarily by increases in: (a) wheat and barley yields, (b) dairy cattle numbers and milk yields per animal, (c) lambing yields, and (d) nitrogenous fertiliser and imported animal feed inputs (Table 3).

4. Discussion

4.1. Evaluation of agricultural indicators used in this review

The indicators used in this review are coarse and can only monitor changes in agricultural management at the national scale. Agricultural activity and the impact of land management practices on local rural communities and biodiversity will depend on a number of factors acting at different scales, i.e. national, regional, farm and field levels (Benton et al., 2003). For example, the nature and extent of historical land use change may have varied significantly between regions.

The national agricultural statistics are partitioned between agricultural sectors and crops. This means that our PCA and overview cannot capture the added dimension of intensification and potential impact on biodiversity and the environment from conversion of land from one form of agriculture to another. For example, the steady increase in the conversion from sheep/beef to dairy farming seen in the last decade represents a general step up to higher input–higher output land use. Conversion of dairy farms to kiwifruit orchards is an example of the reverse trend that would have had far-reaching local consequences for economic, social and environmental sustainability. Inferring net environmental losses or gains from the broad agricultural statistics is therefore dependent on having a better understanding of finer-order impacts of the different farming sectors and crops.

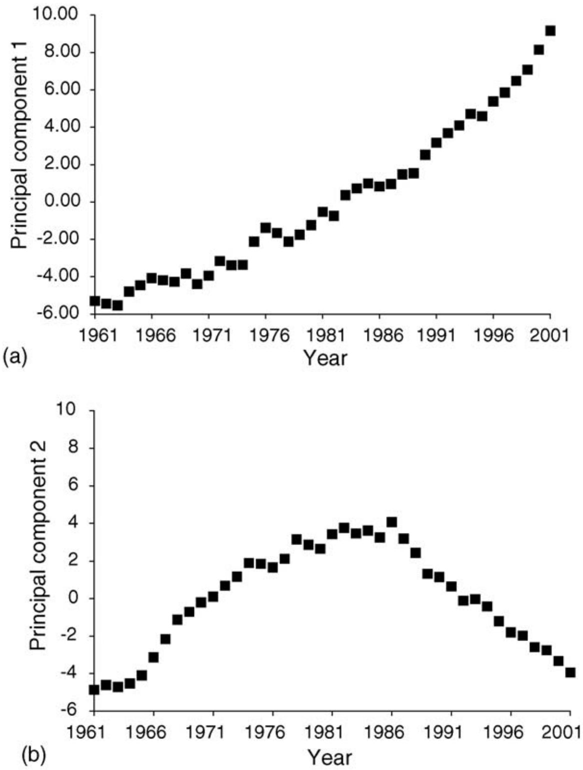

Fig. 7. (a and b) Temporal change in two indices of change in agricultural practices as identified by principal components analysis of 35 variables (Appendix A).

Differential inputs between sectors and crops give some indication that these higher-level consequences from changing land use may be important. For example, patterns of pesticide use vary both between and within sectors of the agricultural industry (Holland and Rahman, 1999). Management practices implemented at the farm level may also vary markedly, from intensive or conventional regimes to non-tillage or organic ones. If these differences in management within each sector and crop have varied historically, the relative environmental impacts of New Zealand agriculture as a whole cannot be tracked closely by the broadly categorised indicators analysed here.

Although the results presented in this paper provide us with a general index of change in agricultural practices in New Zealand over the last four decades, the indicators were selected primarily for their contribution as drivers of overall agricultural production. Very different types of variables are likely to be important in determining the population status of exotic and native flora and fauna in farmland, or measuring the well being of the farming families. The development of a monitoring scheme that provides reliable biodiversity and environmental indicators of the impact of land use changes on native and exotic taxa after the initial large-scale habitat change should be a high priority.

Even if we accept the limitation of indicators from their fundamental productionist orientation, the published measures show evidence of inconsistency and/or errors. Artificial disjunctions in trends were found that cannot possibly reflect real changes on farms. Rather they must relate to changed categorisation in measurement classes. Similar problems are indicated by the way the two main sources for national agricultural statistics used in our review sometimes gave very different results. Although the overall trends in our study match those observed in the recent PCE report, the rates of change in agricultural variables reported in our study tend to be higher (see Table 1 versus Table 3). We recommend a thorough review of past statistics, reconciliation of these divergent indicators, and publication of a detailed description of the basis for past and current categorisation, to facilitate interpretation of trends in the statistics. But perhaps the most important gap in the information we collated was lack of a standardised and more fine-scale delineation of the land area used for sheep,

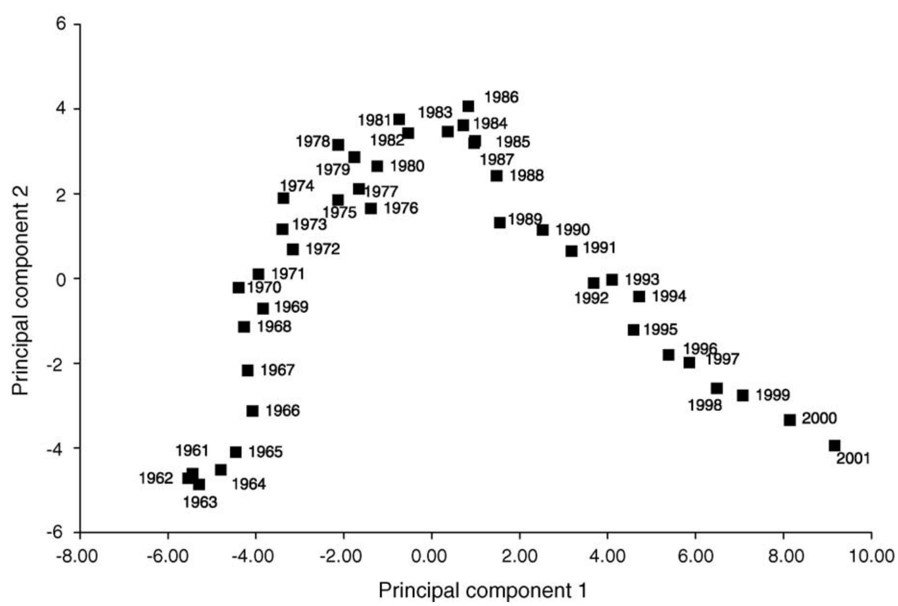

Fig. 8. Ordination (PCA) of years by the 35 agricultural variables described in Appendix A.

Table 3
Annual rate of change (%) for the 35 agricultural variables included in the principal components analysis

Agricultural feature	Variable no.	Variable	Units measured	1961–1981	1981–2001	1961–2001
Land use area	1	Total land occupied (FAO)	Area	0.59	−0.30	0.15
	3	Tilled land	Area	0.86	−0.63	0.11
	4	Plantations	Area	4.54	3.31	3.92
	6	Deer grassland	Area	–	8.38	–
	9	Rough pasture	Area	−0.84	−1.42	−1.13
	10	Improved pasture	Area	1.22	−0.74	0.24
	11	Maize	Area	9.84	−0.88	4.48
	12	Peas	Area	2.25	−1.66	0.30
	13	Potatoes	Area	−0.02	1.09	0.53
	14	Barley	Area	6.05	−1.15	2.45
	15	Wheat	Area	0.34	−2.79	−1.22
	16	Oats	Area	−0.48	−3.26	−1.87
Stock composition	17	Sheep	Numbers	1.83	−2.59	−0.38
	18	Deer	Numbers	–	13.33	–
	19	Beef cattle	Numbers	1.22	0.09	0.65
	20	Dairy cattle	Numbers	0.82	2.24	1.53
	21	Pigs	Numbers	−2.22	−0.88	−1.55
	22	Stock units	Units	1.54	−0.83	0.36
Stocking density	27	Stock units	Units ha^{-1}	1.07	0.11	0.59
Yield per animal	29	Beef and veal	kg $head^{-1}$	2.30	0.28	1.29
	28	Cows milk	kg $head^{-1}$	0.42	1.13	0.78
	30	Mutton and lamb	kg $head^{-1}$	−0.53	0.79	0.13
	31	Wool (greasy)	Greasy kg clip $head^{-1}$	−0.09	0.09	0.00
	36	Lambing rate	% $head^{-1}$	−0.03	0.68	0.33
	38	Barley	tonnes ha^{-1}	1.62	2.09	1.86
	39	Wheat	tonnes ha^{-1}	0.43	2.89	1.66
	40	Oats	tonnes ha^{-1}	2.27	0.72	1.49
Agricultural inputs	41	Non-nitrogenous fertiliser	tonnes	2.14	1.70	1.92
	42	Nitrogenous fertiliser	tonnes	8.14	12.59	10.36
	43	Animal feed imports	tonnes	−4.02	21.06	8.52
	44	Irrigation	Area	4.77	3.15	3.96
	45	Harvester	Numbers	−1.46	−1.49	−1.48
	46	Tractors	Numbers	0.66	−1.17	−0.25
Other indicators	47	Agricultural population	Numbers	−0.03	−0.15	−0.09
	48	Land price	Index	11.09	7.02	9.05

Data are presented for the 20-year periods before and after 1981 separately as well as for the 40-year period overall.

beef, and dairy cattle. This would have allowed a much more cogent analysis of future trends within each of the main sectors of pastoral agriculture in New Zealand.

4.2. *Intensification and diversification signalled by first principal component*

For all the faults and coarseness of the agricultural statistics available, they do collectively indicate a broad scale and continuous thrust to intensification of New Zealand's agriculture over the past 40 years. This trend has apparently accelerated in the past two decades since major reform of the economic and national policies of agriculture in the early to mid-1980s. Our analysis contradicts Langer's (1990) broad characterisation of New Zealand agriculture moving from an intensification to a diversification phase around 1970. It also contradicts other reports that a later phase of intensification began in the 1980s (PCE, 2004). We suggest that major expansion of pastoral systems continued until the late 1970s, and that intensification has been continuous and has accelerated in recent times. There has indeed been diversification of agriculture from the 1970s onwards, but this has been added to the national economic benefits from ongoing intensification of the mainstays of agricultural production (dairy, beef and sheep). Diversification did not displace intensification as the dominant trend. Instead, an ongoing trend for intensification overlapped a period of expansion (1960s and 1970s) and a period of diversification (1970s present day).

Intensification has been described as the process that increases the crop outputs per unit area (Potts, 1997). Available land is the ultimate constraining variable for agricultural output, and when the cost of obtaining and securing it has escalated (Fig. 6), time and energy of farmers has been invested primarily in increasing yield. This intensification has been facilitated by advances in management skills and technology, in particular the introduction of agrochemicals, machinery, and new crop varieties

(Chamberlain et al., 2000; Donald et al., 2001). In the present study, both cereal and livestock production yields were positively associated with scores in the first principal component, indicating intensification.

4.3. Intensification has depended on increased ecological subsidies

The spectacular increase in application of nitrogen fertilisers in the past decade (Fig. 5a) indicates a relatively recent shift away from New Zealand's traditional crop rotation, which used clover to fix nitrogen in the soil (Haynes and Francis, 1990; Williams and Haynes, 1990). There was reduced non-nitrogenous fertiliser consumption just after 1982/1983, but the decline reversed in the past decade and fertiliser use is now increasing again. As most of the phosphate fertilisers have been sourced from Nauru and Christmas Island, two small Pacific islands (Glasby and Wright, 1990), these inputs amount to large and increasing ecological and energy subsidies for New Zealand's agroecosystem over the past 40 years.

The recent escalation of imported livestock foods (Fig. 5b), especially for dairy cattle, is an example of another ecological subsidy from outside the New Zealand agroecosystem. There has also been a general shift towards farms becoming highly dependent on foods from outside the farm but still sourced within New Zealand, in particular increased use of maize and cereal silage (PCE, 2004). If the trend toward increasingly widespread reliance on ecological subsidies in the form of nitrogenous fertilisers and imported animal feed continues, the effect on the local ecology is likely to be profound. Ecological subsidies decouple the stock carrying capacity from the local carrying capacity of the land. Previously the stocking rate reflected greater awareness of and attention to seasonal lows in grass production on the property as well as risk minimisation by conservative stocking to safeguard the farmers' economic sustainability. Buying in food from off-farm sources buffers livestock management from unseasonable lows or extreme interannual events, thereby enabling a much higher year-round stocking rate and resource extraction, although potentially at the cost of increased environmental impacts.

Energy inputs in New Zealand's farming system have probably also increased substantially with intensification. Of particular concern is the system's high dependency on fuel inputs (Wells, 2001). Fossil fuels are currently used for direct inputs of fuel, the manufacture of electricity, and the production of nitrogenous fertiliser. As a significant component of New Zealand's agricultural produce is exported to the international market (PCE, 2004), energy used for transportation of farming produce is also significant. New Zealand's high dependence on fossil fuels for farming means that it is susceptible to changes in availability and prices in fossil fuels (Wells, 2001). This suggests that the current trend for intensification is unlikely to be economically viable in the long term, particularly when fossil fuel supplies become more limited and fuel prices increase markedly. Dependence on high-energy inputs for farming is also not sustainable for environmental reasons such as increased carbon dioxide emissions and the contamination of land with heavy metals from fertilisers derived from oil. Increased reliance on irrigation will result in increased competition for water supplies and increased pollution.

4.4. Intensification has depended on other types of inputs

Pesticide use was not included in the PCA analyses as there were insufficient data available, but there was an indication that pesticide use had increased by at least an order of magnitude over the last four decades. It is not known whether the increases are concentrated on particular land uses or regions. Better monitoring of the types, concentration, number, timing and extent of applications of both fertilisers and pesticides are needed to prioritise research of the potential environmental impact of agrochemicals in New Zealand. Inorganic fertilisers, which have replaced organic manures, are known to increase the concentration of nutrients applied, shorten the nutrient release time into the soil and affect soil chemistry (Chalmers et al., 1990) and pollutant runoff to streams and ground water (PCE, 2004; van Roon and Knight, 2004). The increased use of pesticides and fertilisers supports continuous cropping and reduces the need for weed management techniques such as under-sowing, fallow fields, and crop rotations (Stoate, 1996; Olson and Holland, 1995).

The overall trend for intensification in the pastoral sector appears to be driven by changes in the extent of land use by each sector and yields per animal rather than changes in stocking rates. This suggests that advances in animal science and better application of this knowledge at the farm level have been key drivers of the increase in livestock productivity in New Zealand (Woodford and Nicol, 2005). The probable importance of this type of added input is impossible to quantify from the available statistics.

4.5. Impact of agricultural reforms as signalled by the second PCA axis

The second principal component appears to summarise a period of expansion of New Zealand agriculture up to 1982/1983 and then contraction, especially in the sheep industry. The total area of pastoral land peaked in the early 1980s (Fig. 1b). This was followed by a substantial decline in the area of agricultural land (Fig. 1a) and especially in the total stock units in the system (Fig. 2c).

In New Zealand, deregulation and removal of financial assistance for the farming sector in the mid-1980s are frequently cited as the key drivers of change in the agricultural industry in recent decades (e.g. Wallace and Lattimore, 1987; Sandrey and Reynolds, 1990; Campbell and Lawrence, 2000; Ballingall and Lattimore, 2004). Indeed, our analyses indicate that expansion in agricultural land and the national sheep flock, but decline in sheep farming yields, occurred when the economy was strongly regulated by the government (Dalziel and Lattimore, 2004). During this period, the government aimed to promote full employment by encouraging domestic production, irrespective of New Zealand's ability to compete in the open market. It achieved this through the provision of financial subsidies for farmers and introduction of price and wage regulation policies. Government expenditure increased from the 1960s to the mid-1980s, as it tried to protect the economy from a number of economic crises (e.g. the Wool Price Crisis in late 1960s; the Oil Price Crises in 1973 and 1979; and the removal of the European export market in 1973 when the UK joined the European Economic Community).

Changes in policy from the mid-1980s onwards aimed to reduce direct intervention by the government in the economy and encourage competitive markets to allocate economic resources. Contraction in the area of agricultural land and the national sheep flock associated with an increase in sheep farming yields coincided with this period of major economic reforms. Although this may suggest that economics drive change in agricultural practice, it is probable that each affects the other. Some other third set of variables may also drive change in both economics and agriculture, especially market access and prices. Therefore it would be imprudent to ascribe causation to the way agricultural and economic variables track one another. A more detailed understanding of the agroecological and agroeconomic systems is needed to understand the changes post 1982/1983 and why some sectors were more resilient to change than others. For example, why was the sheep-farming sector more susceptible to changes in the economic and agricultural policy than other sectors such as dairying? Was it simply that the sheep sector was more heavily subsidised? Was the dairying sector more resilient to the reforms or was it able to expand because it had better systems in place to respond to new opportunities?

Our analysis also emphasises that the variables most closely correlated with PC2 had apparently already reached a plateau just before the main reforms took place (Fig. 7b). Were the agricultural changes and potentially associated economic and marketing drivers therefore strong causes of the reforms themselves? Subsidies only contributed up to 5% of the output price of beef and sheep meat between 1970 and 1981, but increased rapidly to over 40% for lamb for the period 1983–1986 (Reynolds and Moore, 1990). Protection of the domestic economy in the 1960s and 1970s, therefore, increased the cost of agriculture to the economy. The plateau in indicators at least 2 years before the first major removal of farm subsidy (the Supplementary Minimum Price subsidy, which was removed in 1984) also raises the question of whether the impact of the subsidies might have been very different had they been imposed in a period of growth? Perhaps the greater impact of the reforms on extensive pastoralism, and sheep farming in particular, may have been in part because they came on top of an immediately prior period of economic retraction. Complex adaptive socio-ecological systems, such as agriculture, may respond differently to shocks according to state conditions at the time of shocks (Berkes et al., 2003).

Although changes in variables strongly correlated with the second principal component must relate to a whole package of economic and policy reforms in the early to mid-1980s, the immediate and temporary economic shock of the agricultural reforms could also have reduced immediate investment in farming. For example, removal of subsidies may have triggered the sharp decreases in non-nitrogenous fertiliser inputs in the 1980s (Fig. 5a) simply because of curtailed farm income. If this temporary shock explanation holds, the PCA analysis suggests that it took 10 years for adjustments to work through the system, because evidence of levelling out of the trend in declining second principal component factors is only evident from 1995 onwards. This raises several competing hypotheses about what drove recovery. Might the less-resilient farm enterprises have been gradually eliminated, leaving only the higher-performing ones to drive national-level industry growth? Did it take even strong farm enterprises 10 years to adjust farm practice to prosper and grow again in the new agricultural policy regimes? Or were external market and macro-economic drivers the key determinants of the duration of the lag? And what sort of learning and adjustment by farmers and their households, rural communities, farm and industry advisors and national-level agricultural policy advisors were associated with the reforms? These and several related questions are part of an overall assessment of the resilience of New Zealand agriculture as part of a long-term search for more sustainable farming (Moller et al., 2005).

The number of people living on farms also correlates with the second principal component of our analysis. The decline in the agricultural population also provides an indicator of the significant changes in the social structure of farm production that occurred during the study period (Campbell, 1994; Campbell and Lawrence, 2000). Levels of family labour increased both on and off farms in the late 1980s, as the landowners could no longer afford to employ other workers. Thus, the proportion of income from off-farm sources increased and the number of unpaid family workers increased (Fairweather, 1992). The correlation hints at a fascinating social dimension to pivotal change in New Zealand farming from the early 1980s.

5. Conclusion: Is New Zealand agriculture sustainable?

Our review highlights the overall and relentless nature of agricultural intensification over the past 40 years. Coarser indicators emphasise that this intensification has proceeded at least for the 80 years before the period we have reviewed (Molloy, 1980; Langer, 1990; Glasby, 1991). Some of the indices of intensification involve increased inputs to the agroecosystem (especially fertilisers and water, but recently also livestock foods) and these may partially or wholly compensate for the increased off take of farm produce. A key question is, therefore, does this trend for agricultural intensification threaten the ecological sustainability of New Zealand agriculture? Case studies elsewhere in the world have highlighted risks to the environment posed by intensification of resource extraction, e.g. dramatic declines in biodiversity in farmland in Europe and North America have been linked to agricultural intensification (Aebischer, 1990; Campbell et al., 1997; Krebs et al., 1999; Donald et al., 2001; Murphy, 2003).

This current trend for intensification in agricultural practices in New Zealand is predicted to continue for at least another decade unless there are major systemic changes (PCE, 2004). The dairy sector, for example, has set a goal to increase productivity by 4% a year so as to gain a 50% increase in total productivity by 2014 (PCE, 2004). There has been no formal published analysis of whether this growth is sustainable from an environmental, social, or even economic perspective.

The challenge therefore remains to assess whether intensification is undermining the natural, social, and economic capital of New Zealand agriculture. It will probably be necessary to develop a combination of studies at the farm, regional, national, and international scales to understand ecological, social and economic dimensions of socio-ecological resilience before sustainability can be assessed. If we are to identify practical solutions to enhance sustainability and resilience, much of the research will have to apply transdisciplinary and farm-management-level focus complemented by a search for appropriate social and economic policies at regional and national levels to promote resilience and sustainability. Our historical review has emphasised the need to understand the overarching importance of a trend to intensification of agriculture in New Zealand, and whether it poses a threat or opportunity for long-term sustainability of New Zealand agriculture. It also emphasises the need for improved and more detailed indicators to help us learn how best to manage farming in New Zealand to realise environmental, social and economic goals of New Zealand society.

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Appendix A

Variables used to assess changes in agricultural practices in New Zealand

Agricultural feature	Variable no.	Variable	Units measured	Years data available	Data source[a]	PCA
Land use area	1	Total land occupied	Area	1960–1997, 2002	Statistics New Zealand; FAOSTAT	FAO only
	2	Total grassland[b]	Area	1961–2001	Derived	No
	3	Tilled land	Area	1963–72,75–86, 88–90, 92, 2002	Statistics New Zealand	Yes
	4	Plantations	Area	1965–1996, 2002	Statistics New Zealand	Yes
	5	Sheep grassland[c]	Area	1972–73, 76–93, 2002	Statistics New Zealand	No
	6	Deer grassland	Area	1972–73, 76–93, 2002	Statistics New Zealand	Yes
	7	Beef grassland[c]	Area	1972–73, 76–93, 2002	Statistics New Zealand	No
	8	Dairy grassland[c]	Area	1972–73, 76–93, 2002	Statistics New Zealand	No
	9	Rough pasture[d]	Area	1960, 66–85, 89, 90, 92, 2002	Statistics New Zealand	Yes
	10	Improved pasture	Area	1960–63, 65–85, 89–90, 92, 2002	Statistics New Zealand	Yes
	11	Maize	Area	1960, 61, 63–86, 88–96, 99, 2002	Statistics New Zealand	Yes
	12	Peas	Area	1960, 61, 63–86, 88–96, 99, 2002	Statistics New Zealand	Yes
	13	Potatoes	Area	1960–86, 88–96, 2002	Statistics New Zealand	Yes
	14	Barley	Area	1960–86, 88–96, 99, 2002	Statistics New Zealand	Yes
	15	Wheat	Area	1960–86, 88–96, 99, 2002	Statistics New Zealand	Yes
	16	Oats	Area	1960–86, 88–96, 99, 2002	Statistics New Zealand	Yes
Stock composition	17	Sheep	Numbers	1960–96, 99, 2002	Statistics New Zealand	Yes
	18	Deer[e]	Numbers	1979–96, 2002	Statistics New Zealand	Yes
	19	Beef cattle[f]	Numbers	1960–96, 99, 2002	Statistics New Zealand	Yes

Appendix A (*Continued*)

Agricultural feature	Variable no.	Variable	Units measured	Years data available	Data source[a]	PCA
	20	Dairy cattle	Numbers	1961–2002	FAOSTAT	Yes
	21	Pigs	Numbers	1960–96, 99, 2002	Statistics New Zealand	Yes
	22	Stock units[g]	Units	1961–2001	Derived	Yes
Stocking density	23	Sheep[h]	Number ha^{-1}	1972–2002	Derived	No
	24	Deer[h]	Number ha^{-1}	1972–2002	Derived	No
	25	Beef[h]	Number ha^{-1}	1972–2002	Derived	No
	26	Dairy[h]	Number ha^{-1}	1972–2002	Derived	No
	27	Stock units[i]	Units ha^{-1}	1972–2002	Derived	Yes
Yield per animal	29	Beef and veal[j]	kg $head^{-1}$	1960–2002	FAOSTAT	Yes
	28	Cows milk[j]	kg $head^{-1}$	1960–2002	FAOSTAT	Yes
	30	Mutton and lamb[j]	kg $head^{-1}$	1960–2002	FAOSTAT	Yes
	31	Wool (greasy)[j]	Greasy kg clip $head^{-1}$	1960–2002	New Zealand Wool Group	Yes
Yield per hectare	32	Beef and veal[k]	kg ha^{-1}	1972–2002	Derived	No
	33	Cows milk[k]	kg ha^{-1}	1972–2002	Derived	No
	34	Mutton and lamb[k]	kg ha^{-1}	1972–2002	Derived	No
	35	Wool (greasy)[k]	Greasy kg clip ha^{-1}	1972–2002	Derived	No
	36	Lambing rate	% $head^{-1}$	1961–78, 80–86, 88–2001	Statistics New Zealand; Woodford and Nicol (2005)	Yes
	37	Calving rate	% $head^{-1}$	1981–2001	Woodford and Nicol (2005)	No
	38	Barley[l]	tonnes ha^{-1}	1960–84, 86, 88–96, 2002	Statistics New Zealand	Yes
	39	Wheat[l]	tonnes ha^{-1}	1960–84, 86, 88–96, 2002	Statistics New Zealand	Yes
	40	Oats[l]	tonnes ha^{-1}	1960–84, 86, 88–96, 2002	Statistics New Zealand	Yes
Agricultural inputs	41	Non-nitrogenous fertiliser[m]	tonnes	1961–2001	FAOSTAT	Yes
	42	Nitrogenous fertiliser	tonnes	1961–2001	FAOSTAT	Yes
	43	Animal feed imports[n]	tonnes	1961–2001	FAOSTAT	Yes
	44	Irrigation	Area	1961–1972, 76, 79, 82, 85, 2002	Statistics New Zealand	Yes
	45	Harvester	Numbers	1960–2000	FAOSTAT	Yes
	46	Tractors	Numbers	1961–2000	FAOSTAT	Yes
Other indicators	47	Agricultural population	Numbers	1960–2001	FAOSTAT	Yes
	48	Land price	Index	1961–2001	Quotable Value (2004), Valuation Department (1985)	Yes

[a] From 1960 to 1970, the Statistics New Zealand surveys only included farms of 4 ha or more, situated outside borough boundaries. From 1971 onwards, the survey covered all farms irrespective of size or location.

[b] Total grassland was calculated as the sum of variables 9 and 10.

[c] Grassland areas for sheep, beef and dairy sectors were estimated by summing all grassland crops within each farm type. For example, beef grassland included those classified as 'beef farms' as well as 'beef farms with sheep' and 'beef farms with dairy'.

[d] Rough grazing was any land classified as tussock or *Danthonia* used for grazing.

[e] We assumed zero farmed deer from 1961 until 1974 and interpolated the increase from zero to 42,080 in 1979 when official counts of the national farmed deer herd started (Challies, 1990).

[f] Beef cattle numbers were calculated as the total number of cattle (Statistics New Zealand) minus the number of dairy cattle (FAOSTAT).

[g] Stocking units were calculated by multiplying each herd/flock size by its respective stocking unit measure. The stocking unit measures were based on the median estimates in Tables 1.72–1.74 of Fleming (2003, pp A-179–A182), with each sheep counting as 1, a dairy cow as 6.5, a beef cow as 4.5 and deer as 1.7 stock units.

[h] These stocking densities were calculated by dividing each national herd/flock size (variables 17–21) by the total area of grassland covered by its respective sector (variables 5–8).

[i] The 'stocking unit' density was calculated by dividing variable 22 by variable 2.

[j] Yields per animal were calculated by dividing the total amount of the item produced by the total number of animals processed or slaughtered.

[k] Yields per hectare for the livestock industry were calculated for by multiplying yield per animal (variables 29–31) for each sector by its respective stocking density (variables 23, 25, 26).

[l] Yields per hectare for the cereal crops were calculated by dividing the total yield produced by each crop (Statistics New Zealand) by the total area of the crop grown (variable 14–16).

[m] Non-nitrogenous fertiliser was calculated as total fertiliser consumption (FAOSTAT) minus nitrogenous fertiliser consumption (variable 42).

[n] Included all 'food stuffs' listed in FAOSTAT database except pet food and soya meal which is imported mainly for pigs and hens.

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