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Intensification of grassland and forage use: driving forces and constraints

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Abstract. The increasing demand for safe and nutritional dairy and beef products in a globalising world, together with the needs to increase resource use efficiency and to protect biodiversity, provide strong incentives for intensification of grassland and forage use. This paper addresses the question: 'Does intensification of grassland and forage use lead to efficient, profitable and sustainable ecosystems?' We present some notions about intensification of agricultural production, and then discuss the intensification of grassland-based dairy production in The Netherlands, Chile and New Zealand. Finally, we arrive at some conclusions.

External driving forces and the need to economise (the law of the optimum) provide strong incentives for intensification, that is, for increasing the output per unit surface area and labour. The three country cases illustrate that intensification of grassland use is a global phenomenon, with winners and losers. Winners are farmers who are able to achieve a high return on investments. Losers are small farmers who drop out of the business unless they broaden their income base. The relationship between intensification and environmental impact is complex. Within certain ranges, intensification leads to increased emissions of nutrients and greenhouse gases to air and use of water per unit surface area, but to decreased emissions when expressed per unit of product. The sustainability of a grassland-based ecosystem is ultimately defined by the societal appreciation of that system and by biophysical and socioeconomic constraints.

In conclusion, intensification may lead to more efficient and profitable and, thereby, more sustainable grassland ecosystems. This holds especially for those systems that are currently not sustainable because they are either underutilised and of low productivity or over-exploited and unregulated, and as long as the adapted systems meet societal and ecological constraints.

Additional keywords: dairy farms, GHG emissions, nitrogen, resource use, technological progress, yield gap.

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Introduction

Global food security and environmental sustainability are major scientific and political issues (e.g. Smil 2000; Sachs 2008; Godfray *et al.* 2010). Food production will have to increase by >50% to be able to feed the expected 20–40% additional people in the world by 2050 (Parry and Hawkesford 2010; Alexandratos and Bruinsma 2012). The shifts in human diet towards more animal-derived food and the increasing demand for bio-energy production add to the challenges of food security. In addition, the need to curb the negative effects of food production on the environment is increasingly evident, because of the large and increasing contributions of current food production systems to biodiversity loss, climate change, land degradation, and water pollution in many areas (Steinfeld *et al.* 2006, 2010; Galloway *et al.* 2008). To ensure global food security with environmentally sound practices, food production and resource use efficiency must be increased simultaneously (Tilman *et al.* 2002; Godfray *et al.* 2010).

Grasslands are an interesting case in this regard. Grasslands are among the largest ecosystems in the world, with an estimated area of 52 million km^2, equivalent to 40% of the global terrestrial area (McGilloway 2005; Suttie *et al*. 2005). Almost 34 million km^2 is used for agriculture, equivalent to 68% of the total agriculturally utilised area in the world (FAOSTAT 2013). These grasslands provide feed to billions of cattle, sheep and goats. Global milk and beef production have both increased by ~5% per year during the last 50 years, whereas grassland (and arable land) areas have not increased much (<10% in 50 years). Forecasts indicate that the intensification of grassland use has to increase significantly to meet the growing demands for dairy products and beef during the next 30–50 years (Alexandratos and Bruinsma 2012). If we wish to reduce the total environmental footprint of grassland and forage use, then resource-use efficiency will need to increase at a faster pace than production increases.

This paper addresses the question: 'Does intensification of grassland and forage use lead to efficient, profitable and sustainable ecosystems?'[1] Our shortest answer to this question would be: 'Yes, but not necessarily.' Of course, if we view the trend lines in production of main commodities during the last 50 years (Smil 2000; Evenson and Gollin 2003), we can be rather optimistic, but at the same time, there has been a massive exodus of farm labour, remaining malnutrition is overwhelming, emissions of greenhouse gases (GHG) and other unwanted emissions have increased (e.g. Steinfeld *et al.* 2006), public perception and acceptance of certain production methods is diverse and changing (e.g. Pollan 2006), and there are clear examples of our inability to manage ecosystems properly (e.g. Diamond 2005). Another reason for our qualified answer is the huge diversity of grasslands in the world. This diversity means that intensification might have different effects in different grasslands. Most of the world's grasslands are on poor-quality land and are highly vulnerable, which makes them less suited to intensification. A third reason is the versatile meaning of the words in the question posed above. 'Intensification', 'efficient', 'profitable', and 'sustainable' are often perceived differently by different people and, for meaningful discussions, therefore need to be defined operationally. There is a common notion that these terms are more easily defined in relative terms (from less to more and *vice versa*) than in absolute terms. Another notion is that these terms are contextual, that the meaning and rating greatly differ between systems, regions and between individual farms or farmers. Here, we define these terms briefly as follows. Intensification is 'increasing marketable output per unit surface area and/or per unit labour'; efficient is 'high marketable output per unit of input'; profitable is 'monetary value of output exceeds total costs of inputs'; and sustainable is 'a combination of economically profitable, socially acceptable and environmentally sound, for now and later' (e.g. de Wit 1992; Cassman 1999; Garnett and Godfray 2012). A fourth reason for our qualified answer relates to the difficulty of defining 'ecosystems' (e.g. Sagoff 2003). We distinguish natural ecosystems and agro-ecosystems. Both are controlled by external (e.g. climate) and internal (e.g. soil and plant characteristics) factors, but the influence of human activities is dominant in the case of agro-ecosystems.

In this paper we explore biophysical, socioeconomic and environmental drivers of, and constraints to, intensification of grassland and forage use and discuss how these drivers and constraints affect the development of agro-ecosystems. We focus on grassland-based dairy production in three countries across three continents: Chile, The Netherlands (NL), and New Zealand (NZ). First, we present some general notions about intensification of agricultural production. Next, we present empirical data about intensification of grassland-based dairy production in Chile, NL and NZ. We close by providing a more definite answer to the general question of this paper.

Intensification of grassland and forage use: some conceptual notions

Driving forces and biophysical limits

Intensification of agricultural production in general, and of grassland and forage use in particular, is a complex process, as it has many driving forces, bio-physical, socioeconomic and environmental constraints, and often unintended consequences. Intensification is a result of technological progress, which is fuelled by developments in markets, technology, and/or policy (Fig. 1). These developments provide tools for technological progress, including improvements in knowledge, management, mechanisation, and in herbage and animal breeds. Commonly, there is also a change in inputs such as fertilisers, concentrate feed, herbicides, veterinary assistance and contractor assistance. Technological progress leads to changes in the utilisation of grassland and forage, which subsequently leads to higher yields per ha and per unit labour, and to changes in various emissions. The resulting changes in productivity, efficiency and farm income may subsequently lead to changes in farm structure and in the price ratio of outputs and inputs, which may provide new impetus to intensification. Hence, intensification of grassland and forage use involves a chain of processes. The outcome is often region- and farm-specific, because of intrinsic differences between regions and between farms.

Yields of grassland are ultimately constrained by yield-defining, yield-limiting and yield-reducing factors (Fig. 2). In practice, there are large gaps between potential yield, water- and nutrient-limited yield, and actual yield (e.g. Lobell *et al.* 2009; Mueller *et al.* 2012). These gaps provide the incentive and justification for the intensification of grassland and forage use. The potential yield depends on the genetic traits of the crop and climatic conditions. Intensification of grassland narrows the gap between potential and actual yields, and may increase the potential yield through the use of plants with higher genetic merit. Evans (1993) defines potential crop yield as the yield of a cultivar when grown in environments to which it is adapted, with nutrients and water non-limiting, and with pest, diseases, weeds, lodging and stresses effectively controlled. Soil features are also possible yield-limiting factors (Fig. 2), because, in addition to water and nutrients, soil depth, slope, texture and hydrology may limit yield. It has been suggested that intensification of cereal production is possible until actual yields are, on average, 70–80% of the potential yield (Cassman 1999). Grassland and forage crops have a relatively high yield potential, due to the long growing period, existing root system, and whole-crop harvest (e.g. Evans 1993; Murphy 2005; Glover *et al.* 2010), but growth and regrowth cycles are very sensitive to management (e.g. Slewinski 2012). However, there is little quantitative information about the gap between potential and actual dry matter yields of grassland in practice. Herbage is an intermediate product, used to feed ruminants and to produce milk and beef. The available statistics on dairy and beef production do not include information about herbage

[1]This topic was suggested by the organizers of the 22nd International Grassland Congress, Sydney, Australia, 15–19 September 2013. This paper is a modified version of the keynote address presented.

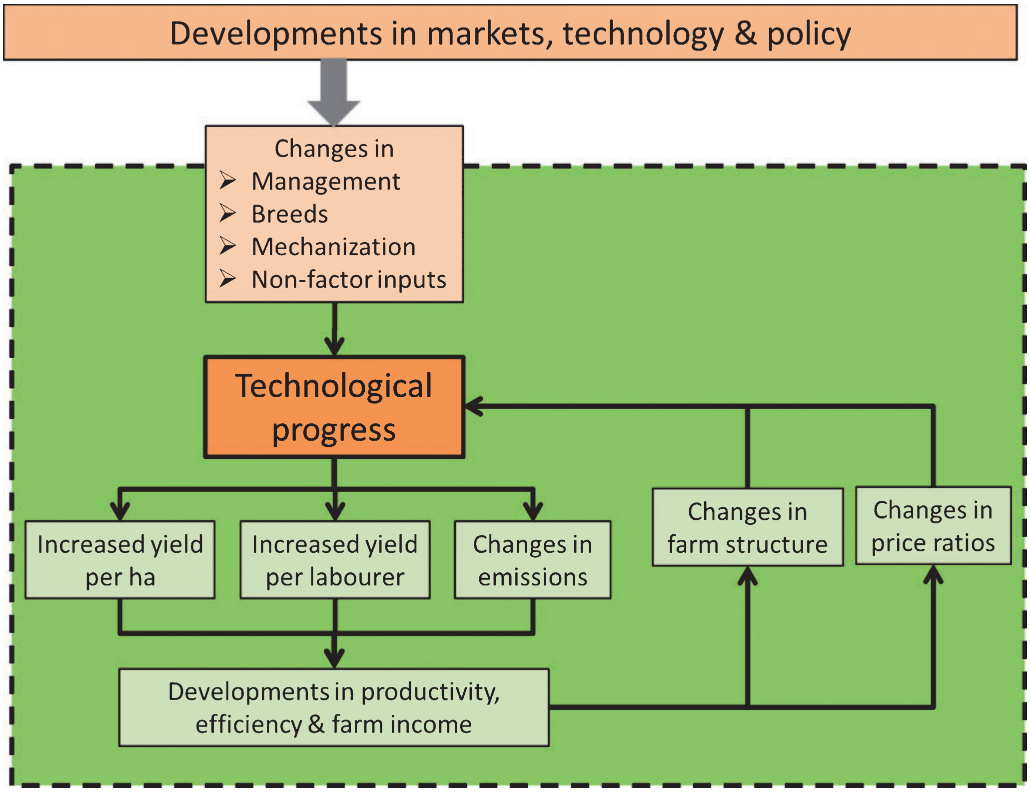

Fig. 1. Concept of intensification of grassland and forage use, as used in this paper. External driving forces are at the top. Arrows represent influences and/or incentives; boxes represent processes or results.

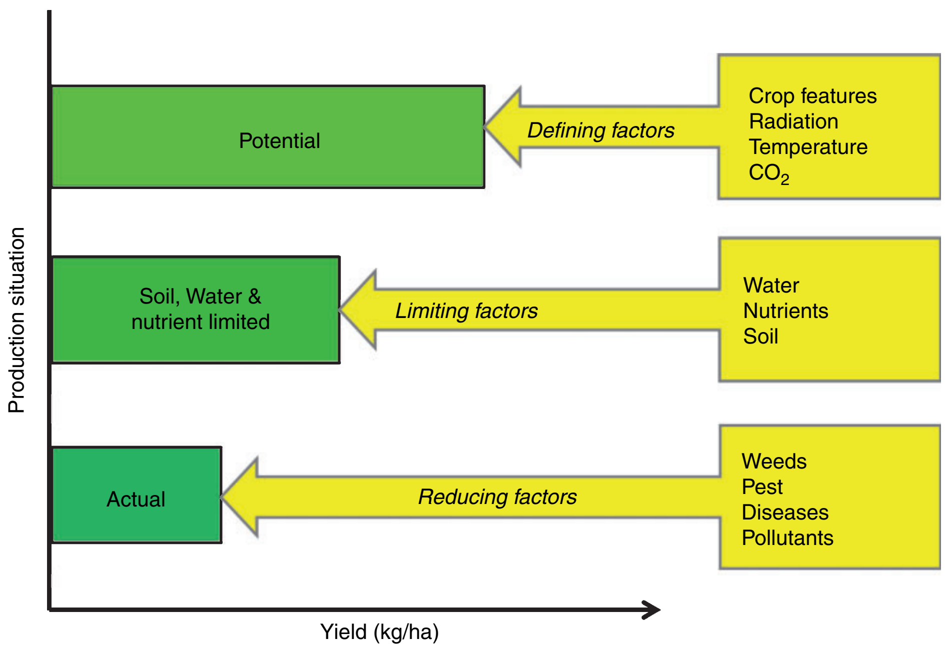

Fig. 2. Yields of grassland and cropland are the results of interactions between yield-defining factors, yield-limiting factors and yield-reducing factors. After van Ittersum and Rabbinge (1997).

production. As a consequence, there is no accurate statistical information about grassland yields in practice.

The production ecological concept of yield-defining, -limiting and -reducing factors for grassland and cropland in Fig. 2 also holds for animal production systems. Here, yield-defining factors are animal species, breed and sex, and temperature, while yield-limiting factors are the availability and quality of feed and water. Main yield-reducing factors are diseases, animal wellbeing concerns and pollutants (van de Ven *et al.* 2003). There is much information about differences between regions and farms in actual yields of dairy and beef production systems, but there is little information about the gap between potential and actual yields in practice. Yield potential is difficult to measure, but simulation models can provide reasonable estimates of functional yield potentials in a given environment, based on physiological relationships that govern plant and animal development and growth (e.g. Cassman 1999).

In practice, animal production is constrained by biophysical limits, and by environmental, economic and societal limits (e.g. Steinfeld *et al.* 2010). Intensification of animal production may be achieved through a change in system (Fig. 3). Higher yielding systems are often more complex and require more management skill and inputs such as energy, fertilisers, feed and veterinary assistance. Figure 3 shows that animal protein output per unit of surface area may differ by >4 orders of magnitude between systems. Whereas animal production in pastoral systems and grassland-based beef production largely depend on the primary production of the grassland, animal production in feedlots completely depends on purchased animal feed. This holds to some extent for intensively managed, grassland-based dairy production systems; these systems import fertilisers to boost herbage production and import supplementary feed from other countries to boost milk and beef production. The shift in system is also a result of technological progress and changes in market and institutional arrangements, which affect the farm structure (Fig. 1). The term 'farm structure' refers here to the type, size, organisation and ownership of the farm.

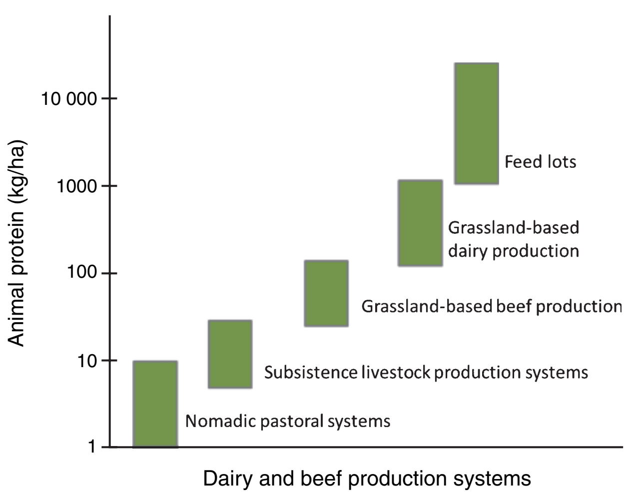

Fig. 3. Comparison of animal protein production levels of various beef and dairy production systems. Developed for the purpose of this paper, based on Smil (2000). Note logarithmic scale of *y*-axis.

All systems depend on natural resources such as plant and animal traits, photosynthetic radiation, carbon dioxide (CO_2), water and nutrients (Fig. 2). Similarly, the law of diminishing returns holds for all systems, although yields may differ by 4–5 orders of magnitude between systems. Evidently, the decrease in marginal returns with an increase in resource input, as predicted by the law of diminishing returns, is compensated by the benefits of other technological changes when the system is changed (de Wit 1992). Resources are used more efficiently with increasing yield level, due to further optimisation of production conditions according to 'the law of the optimum' (de Wit 1992). This is a strong internal driving force for intensification. Intensification of agricultural production is driven not only by the quest for more food for the growing global population, but also by the need to lower production costs and resources use, and to increase farm income. This will ultimately lead to more efficient utilisation of resources. With the intensification of animal production along the trajectories discussed in Fig. 3, an increasing number of inputs gradually lose their variable character (de Wit 1992).

Environmental side-effects

Possible side-effects of intensification relate to increased resource use and increased emissions of unwanted substances per unit of surface area. Dairy (and beef) production systems are major emitters of the GHGs methane (CH_4), nitrous oxide (N_2O) and CO_2. Emissions of CH_4 (mainly from ruminants) account for roughly half of the total GHG emissions from dairy production, when expressed in CO_2-equivalents. Emissions of N_2O (from soils and manure management) and CO_2 (from energy combustion and soils) each account for roughly 25% of the total GHG emissions from dairy production (FAO 2010). Emissions expressed in mass per unit surface area generally increase with intensification of production (Fig. 4), but this picture is often reversed when emissions are expressed per unit of product. For example, Van Groenigen *et al.* (2010) showed that yield-scaled N_2O emissions are lowest around optimal N fertilisation levels, where crop yields are near maximum attainable yields. Both suboptimal and over-optimal N fertilisation leads to higher N_2O emissions per unit of crop produced. The same is often true for nitrate (NO_3^-) leaching from pastures and ammonia (NH_3) emissions from animal manures. However, losses of N via NO_3^- leaching and NH_3 emissions from dairy production systems also depend on climate, soil type and management, making the relationship with intensification of grassland and forage use often complex and diffuse.

Methane emissions from dairy production are related to feed intake; on average, 4–7% of the gross energy intake is lost as CH_4. Increasing the quality of feed, especially roughage, and increasing milk production per cow can reduce enteric CH_4 production per unit of milk because of the relative decrease in maintenance cost. Emissions of CH_4 decrease on average by 0.4–0.5 g/kg milk when milk yield per cow increases by 1 kg. Hence, intensification through increasing milk yield per cow lowers CH_4 emissions per kg of milk produced (Flysjö 2012; Fig. 4). Similarly, energy-use-related CO_2 emissions tend to increase with intensification of grassland and forage use,

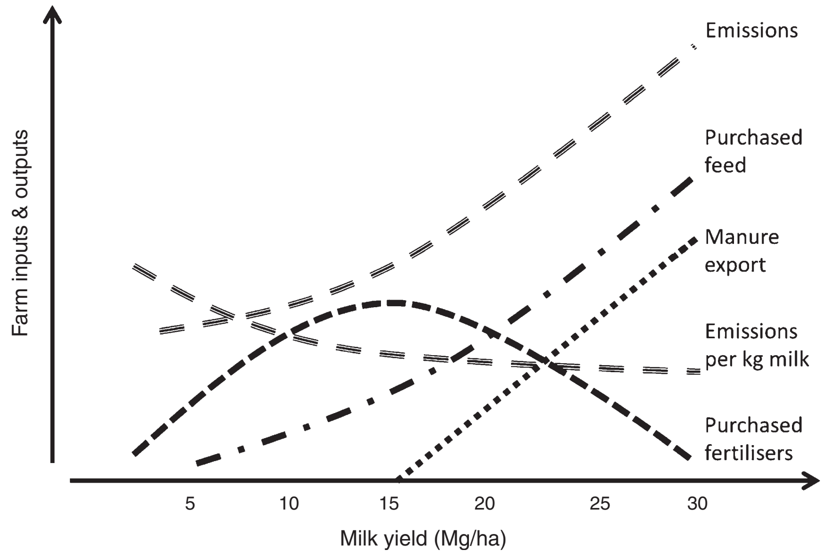

Fig. 4. Conceptual relationships between milk yield per ha and purchased feed and fertilisers, required manure exports and emissions of greenhouse gases and nutrients (see text).

because of greater use of resources and mechanisation. However, emissions per unit of forage or milk produced may not necessarily increase; this depends on the specific system and labour availability.

Increasing milk and/or beef yield beyond the level where the import of nutrients in purchased feeds is higher than the export of nutrients in dairy and beef products leads to the accumulation of these nutrients and an increased risk of their losses to the wider environment. This is the case in feedlots, but also in intensively managed, grassland-based systems, which rely on import of purchased feedstuff. With an increase in the import of purchased feedstuff, the need for purchased fertilisers decreases because the nutrients in produced animal manure may largely cover the nutrient demand by the grassland and forage crops (Fig. 4). Increasing milk production beyond a certain level will require the export of animal manures to prevent excessive accumulation of phosphorus (P), potassium (K) and micronutrients such as copper (Cu) and zinc (Zn) in soil, and to prevent excessive concentrations of nitrogen (N) in groundwater and surface waters (e.g. Menzi *et al.* 2010). The export of animal manures, with or without prior processing, to other farms can be costly and may constrain the intensification of grassland-based dairy production between 10 000 and 20 000 kg milk/ha.year, depending on grassland productivity.

Social side-effects

In their 'History of World Agriculture', Mazoyer and Roudart (2006) argue that in a globalising world (*i*) modern farms in the western world compete on the world market with small subsistence farms elsewhere; (*ii*) the productivity per ha and per unit labour increases due to technical progress, but much more in the western world than in the developing world; (*iii*) prices for agricultural commodities decrease due to technical progress and increased competition; (*iv*) cost of living increases because of higher standards and inflation; and (*v*) farmers with low productivity drop out, whereas new, more productive farms develop further on the other side of the spectrum. These lines of thought are visualised in Fig. 5, which conveys the message that intensification, upscaling and increasing labour productivity is the only way to stay in production in a globalising world. Of course, this statement is too simple, as there is also a third axis, not shown in Fig. 5, the axis of creating 'added value' and additional income sources. Production and marketing of 'farmer-made cheese', landscape maintenance, tourist housing, and care for disadvantaged and disabled people may provide additional income sources for the farmer, especially in rich and densely populated countries (Van der Ploeg 2009).

The sustainability of intensive production systems is also constrained by its social acceptability (e.g. Pollan 2006; Scholten *et al.* 2013; Bos *et al.* 2013). Social acceptability may differ greatly between countries. For example, genetically modified soybean and maize in animal feed, and use of recombinant bovine somatotropin (rbST) in dairy production, are common in the Americas, but they are not accepted in Europe. Also, changing notions about animal welfare increasingly force farmers in Europe to adjust stables and promote grazing instead of zero-grazing.

In summary, intensification of grassland-based dairy and beef production has strong external and internal drivers. It is a global and non-linear process, which leads to the evolution of systems and to exodus of smallholders in, and abandoning of, less competitive areas, which is a concern in many areas of the world because of the livelihood of rural areas (e.g. MacDonald *et al.* 2000; Steinfeld *et al.* 2010). Relationships between intensification of grassland and forage use, and agronomic and environmental performances, are complicated by the effects of climate, soil type and management. Intensification of production is a mainstream in current society for feeding the growing human population, although there is also much to gain from decreasing food wastes and food losses, and from changing human diets (Garnett and Godfray 2012; Westhoek *et al.* 2014). The question here is where and how far to intensify production. Below, we discuss three case studies, i.e. Chile, NL and NZ, to illustrate further the concepts and constraints described above.

Characterisation of grassland and forage use in Chile, The Netherlands and New Zealand

General overview

Although greatly differing in location, area, geography and population density, Chile, NL and NZ have in common large areas of productive grasslands and an export-oriented, grassland-based dairy production (Table 1). Inherent to diversity in geography and climate, the diversity in grassland and dairy production systems is much greater in Chile than in NZ and especially NL. Also, the trajectories of the intensification of grassland use differ greatly; the intensification is more recent in Chile than in NZ and especially NL. As a result, milk yield per cow and per ha of grassland are lower in Chile and NZ than in NL (Table 1).

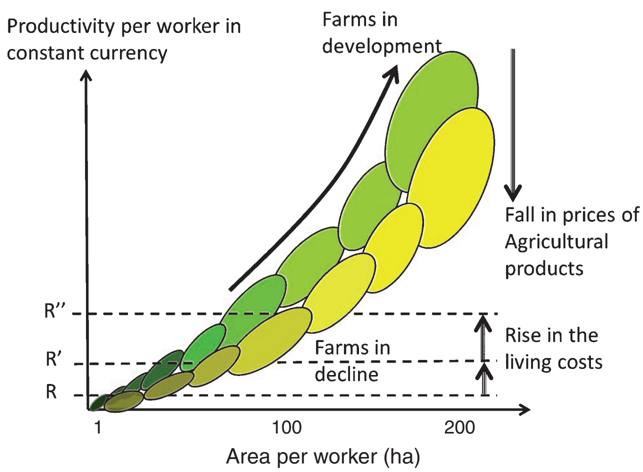

Fig. 5. Comparison of productivity per worker for various farming systems in the world. Subsistence farms and small farms are situated in the lower left corner, highly mechanised large farms in the upper right corner. Over time, the productivity per worker expressed in constant currency drops down, due to a fall in the prices of agricultural products, visualised by a change from green-coloured to yellow-coloured farming systems. At the bottom, farms are in decline, because the cost of living goes up from R to R′ and R″, i.e. the point of marginalisation moves upward (after Mazoyer and Roudart 2006).

The increases in number of cattle in Chile, NL and NZ largely parallel the increase in world cattle numbers between 1961 and 2011 (Fig. 6). However, cattle number decreased in NL from 1984 onwards because of the implementation of a milk quota system and steadily increasing milk yield per cow (1–2% per year). Sheep were increasingly replaced by dairy cattle in NZ from the 1990s, and the number of milk goats increased in NL from 1984 onwards (goat milk was not under the milk quota system). From the 1990s, total milk production in NZ and Chile showed a greater rate of increase than world milk production, whereas milk production in NL remained stable. The specialisation in milk production is reflected indirectly in a less than proportional increase in beef production in Chile, NL and NZ compared with world beef production. Beef production in NL decreased from 1990s onwards, mainly due to a decrease in policy support. The differences in mean milk production and mean beef production per unit of agriculturally utilised grassland area (meadows and pasture according to FAOSTAT 2013) among Chile, NL and NZ are shown in the two bottom panels of Fig. 6. While mean milk and beef production per ha is rapidly increasing in Chile and NZ, the overall mean is still much lower than in NL. However, the land areas used for producing the purchased feedstuff are not included here, indicating that a direct comparison of the milk and beef production per ha between these countries is biased (Taube *et al.* 2014). Yet, the difference also reflects that Chile and NZ have large areas of extensively managed grasslands (rough

Table 1. General characteristics of agriculture and dairy production in Chile, The Netherlands and New Zealand in 2010
Sources: FAOSTAT (2013), INE (2012), LEI/CBS (2012), New Zealand Dairy Statistics (2012)

Characteristics	Chile	The Netherlands	New Zealand
Total surface area (Mha)	76	3.5	27
Agricultural area (Mha)	15.8	2.1	11.4
Grassland area (Mha)	14.0	1.0	10.8
Human population (millions)	15	17	4
Dairy cattle (millions)	1.5	1.8	6
Other cattle (millions)	2.3	2.1	4
Sheep and goat (millions)	4.4	1.5	33
Milk production (billion kg)	2.6	11.5	17.3
Export dairy production (%)	15	60	90
Herd size (no. of cows/farm)	26	78	380
Milk yield (kg/cow)	4700	8100	3800
Milk fat and protein (g/kg)	72	79	85
Milk yield (kg/ha) (mean ranges)	3000–15 000	8000–25 000	5000–15 000
Dairy production systems	Low-input	High-input	Low-input
Main drivers for intensification	Market prices	Market prices, policy support	Market prices
Intensification strategies	Increasing area, more cows per ha, more milk per cow	More milk per ha, more milk per cow	Replacing sheep with cows, more cows per ha, more milk per cow
Current limits to intensification	Milk prices, technology transfer	Milk quota, environmental regulations	Herbage yield, land prices
Foreseen limits	Biodiversity nutrient losses	Manure export, nutrient losses, GHG emissions	GHG emissions, nutrient losses

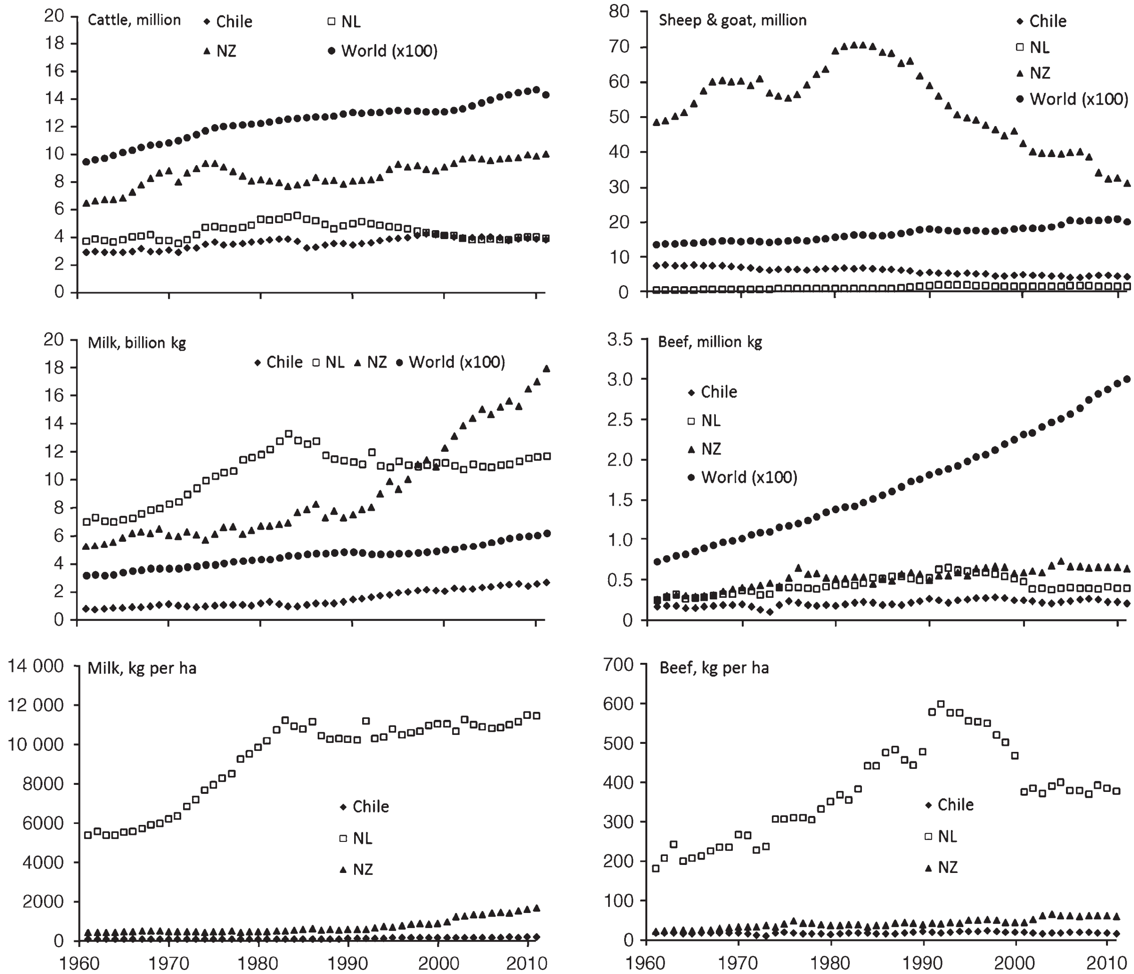

Fig. 6. Changes in number of cattle and sheep and goat (upper panels), total milk and beef production (central panels), and milk and beef production per ha, in Chile, the Netherlands (NL) and New Zealand (NZ) between 1961 and 2011 (FAOSTAT 2013, retrieved December 2013). Note that values for World are 10^{-2} of actual.

grazing), and a much smaller fraction of intensively managed grassland than NL.

All three countries have applied similar strategies for the intensification of grassland and forage use, but at different rates and extent (Table 1). More cows per ha, more milk per cow, and increasing the area of grassland and forage land have all contributed to the increase in milk and beef production. Grassland area in Chile has increased by ~30% during the last 50 years, at the expense of natural vegetation, whereas some grasslands in NL were converted to silage maize production. All three countries also face limits to further intensification of grassland and forage use. Market prices for milk currently constrain dairy production in Chile; land prices and consent to convert forest into pasture and, hence, herbage yield constrain dairy production in NZ; and milk quota and governmental regulations related to manure application and N and P losses limit dairy production in NL. In the foreseeable future, Chile and NZ may also face environmental regulations that constrain intensification of grassland and forage use (Table 1).

Chile

Chile extends from the Atacama Desert in the north to Patagonian rangeland in the south (4300 km). The central part of Chile is dominated by a Mediterranean climate with a mean rainfall of 300–1000 mm/year. Further south, the country is dominated by a temperate climate, with mean rainfall of 1300 and 2500 mm/year. Dairy production is mainly found at 32–42°S and beef production further south at 40–56°S. Eight dairy production zones are distinguished in Fig. 7. Around 4 Mha of grassland is used for beef production, 1.5 Mha for 474 000 dairy cows, and another 8 Mha for rough grazing of sheep (FIA 2008; INE 2012). Intensive dairy systems (feedlots) are found in the central part of Chile, whereas grazing systems dominate in the south (FIA 2008). The latter produce two-thirds of all milk in Chile. Holstein–Friesian dairy cows are found on the more intensive systems. These animals have higher demands in terms of feed quality and management than the local, rustic breeds. The dairy systems in the central part of the country (zone 1) are more vulnerable to changes in feed and milk prices than the grassland-based dairy systems further south, because the

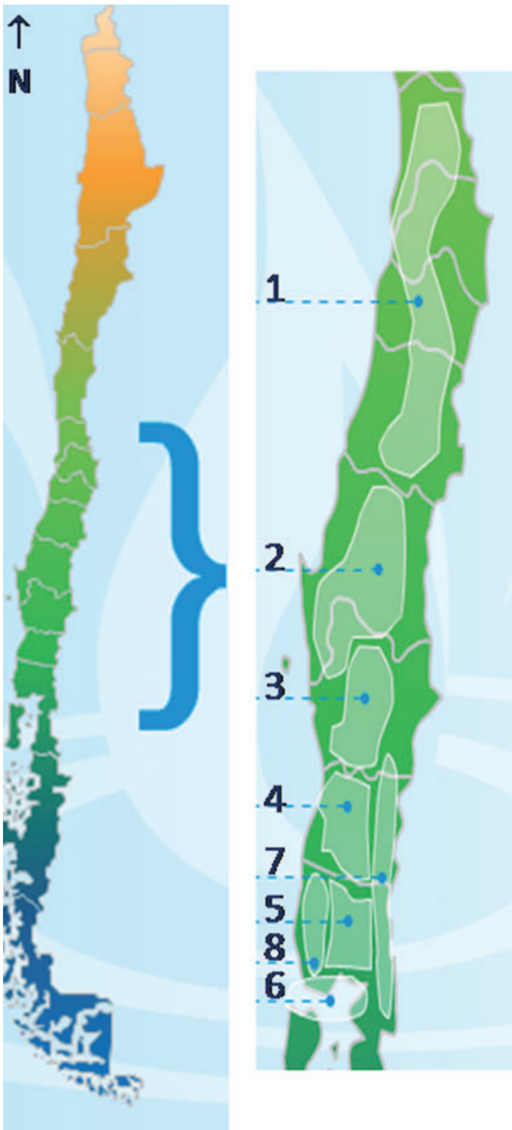

Fig. 7. Distribution of dairy production zones in Chile. Numbers refer to the eight regions with dairy production systems (Consorcio Lechero 2012).

former have a much larger percentage of purchased feeds. The cost of milk production is 30–40% higher in the intensive systems in zone 1 than in the grassland-based systems further south. The frequency distribution of farm size is highly skewed; 70% of dairy farms have <10 cows, the largest 10% of farms have almost 80% of the dairy cows and produced 90% of all milk in 2010.

From 1985 to 2010, milk production increased at mean rate of 60 million kg/year, in response to the development of the export sector, which has grown by 23% during the period 1998–2007. The milk price paid to farmers is highly correlated with that of the world market, which increased, on average, by 7.5% per year during the last 10 years. The intensification of the dairy sector is expected to continue in coming decades. The current internal economic and political stability and the potential for intensive, grassland-based dairy production have also attracted foreign capital, and these foreign direct investments have contributed to the development of the dairy-processing industry.

Intensification of dairy production has been made possible through increased pasture productivity, that is through reseeding, fertiliser applications, rotational grazing and increased pasture utilisation (Alfaro and Salazar 2005; Alfaro *et al.* 2008; Núñez *et al.* 2010). Application of fertiliser P to pastures on the dominant (~90%) low-P volcanic soils has greatly contributed to increased pasture productivity (Escudey *et al.* 2001). Use of supplementary crops (e.g. turnip) to overcome temporary herbage shortages during dry periods has also been helpful. Current pasture production in intensively managed dairy systems has been estimated at 50–80% of the attainable dry matter yield, as established in field experiments (15 000–18 000 kg/ha.year). This suggests that further intensification of grassland use is possible.

Measured NO_3-N leaching losses (10–90 kg/ha.year; Núñez *et al.* 2010; Salazar *et al.* 2012*a*) and N_2O-N emissions (<0.2 kg/ha.year; Vistoso *et al.* 2012) are comparable to, or slightly lower than, those of similar systems in other regions of the world. The relatively low N losses may be related to the physicochemical characteristics of the volcanic soils and the relatively young age of the pastures, which tend to adsorb nitrate and accumulate organic N, respectively. In addition, on most farms, a considerable proportion of the area (10–40%) is still woodland or shrubland, which contributes to landscape diversity and carbon sequestration, and acts as a buffer for larger natural areas (FIA 2008). Although direct P losses have been estimated to be low (<80 g P/ha) (Alfaro and Salazar 2007), there is an increasing risk of surface water pollution when high P inputs continue. Slurries collected during confinement are temporarily stored in open ponds and then surface-applied to pastures (at an N application rate of $\leq$40 kg/ha.year; Alfaro *et al.* 2008). Total ammonia (NH_3) volatilisation losses from urea fertilisers and cattle slurry are in the range of 20–50% of the amounts of N applied (Salazar *et al.* 2012*b*). These high losses have economic impacts for farmers, but there are no other incentives to reduce these losses.

Chile is renowned for its biodiversity, beautiful landscapes, and pristine air and water quality, and the further intensification of dairy and beef production may have serious environmental impacts. These natural resources are also being used by other economic sectors (aquaculture, tourism). Currently, there is a fragile balance between intensification of dairy and beef production and maintaining the high natural values of the lake, forest and shrub ecosystems.

The Netherlands

Agricultural development in NL is strongly related to its geographical situation and to the European Union with its Common Agricultural Policy, which have boosted agricultural production. Apart from intensive dairy production on 60% of the agriculturally utilised area, there is intensive production of vegetables, bulb flowers, nursery trees, potatoes, sugar beet and wheat on the other 40% of the area. In addition, there are 13 million pigs and 100 million chickens on mostly landless farms. As a result, NL is the second largest exporter of agricultural products in the word.

Milk yield per unit surface area increased from 2000 kg in 1900 to 13 000 kg/ha.year in 2010 (Bieleman 2008), but with a large variation between farms (range 8000–25 000 kg/ha). The strongest intensification occurred between 1960 and 1984; thereafter, grassland and forage use has been constrained by milk quota, installed by the European Commission to lower the milk production surplus in the European Union and the cost of its disposal. The main tools for intensification of grassland and forage use were subsequently: soil drainage; fertilisation; improved grazing and mowing management; reseeding grassland with high-yielding varieties; increased selection and breeding for high-yielding dairy cows; feed supplementation; replacement of grassland by forage maize; improved herd and disease management; precision feeding, in part through stall-feeding and zero-grazing; milking robots and switching from two to three milkings per day; and increasing farm size.

Grassland yields have increased less than milk yield during the last few decades. The gap between feed requirements and feed production was closed by increasing the amount of purchased concentrates. Mean concentrate use was 2100 kg/cow.year in 2010, i.e. roughly one-third of the energy requirements. There is little empirical information about herbage yields in practice. Estimates suggest that mean harvested yield was ~4000–5000 kg/ha.year in early 1900, ~6000–7000 in the 1970s, and 9000–11 000 kg/ha.year in the 2000s (Bieleman 2008; Oenema *et al.* 2012). Variations between farms and between years are large. Differences between farms in the utilisation of grassland are related to the milk yield per ha, and hence to the demand for herbage, but also to soil type and grassland management. Mean dry matter yield in field experiments that were not limited by nutrients was ~15 000 kg/ha.year during the last few decades (Vellinga and André 1999), suggesting that farmers achieve 60–80% of attainable yield. Hence, the scope for further intensification of grassland use is rather modest.

From 1984, dairy farmers have had to cope with (tradable) milk quota and with government policies related to nutrient management and NH_3 emission mitigation. There are soil-type-specific manure and fertiliser N and P application measures for grassland and forage land, and strict regulations for low-emissions animal housing, manure storage and manure application. These regulations have decreased the N and P surpluses and NH_3 emissions by >50%. Fertiliser N use decreased by 50–80% and fertiliser P use decreased by almost 100%. Dairy farms producing >14 000–18 000 kg milk/ha.year cannot dispose of all produced animal manure on their own farmland within the set application limits, and have to export the surplus manure to other farms. The cost of manure (cattle slurry) export ranged from €10 to 25/m^3 (AU$15 to 39/$m^3$) during the last 5 years, depending on transport distance, season and prior processing. This translates to €260–650 per dairy cow producing annually ~8000 kg milk and 26 m^3 manure. By comparison, low-emission slurry spreading on own farmland ranged between €2.5 and 3.5/m^3 in 2010, depending on the contractor and transport distance. Manure disposal off-farm seriously constrains the intensification of grassland and forage use beyond milk production levels of 14 000–18 000 kg/ha.year, and requires that the animal manures are collected in housing systems and stored in leak-tight and covered storage systems.

The milk quota system will be abolished in 2015. There is no longer surplus dairy production in the European Union and world market prices for milk are higher than internal milk prices. Unlike most other countries in the European Union, many dairy farmers in NL have anticipated the abolition of the milk quota system, and have already enlarged farm area and buildings, and hence made investments. Forecasts suggest that total milk production will increase by ~15% in 2015. The investments have also increased the price of land, which ranged from €30 000 to 75 000/ha depending on the quality of the land in 2010 (LEI/CBS 2012), and have increased the cost of producing 1 kg milk. The increasing size of dairy farms has also provoked debate about so-called 'mega-stables' (Breeman *et al.* 2013); these farms with >300 dairy cows are criticised for deteriorating the amenity of the countryside.

Most dairy farms have a so-called derogation (exemption) from the application limit of 170 kg/ha.year of manure-N on grassland, as stipulated in the EU Nitrates Directive. These farms may apply up to 250 kg/ha.year, but under additional restrictions. A representative sample of 270–300 dairy farms (of ~20 000 dairy farms with derogation) is intensively monitored, and the results are reported annually to the European Commission. Results for the year 2012 indicate that 25–50% of the dairy farms on nitrate-leaching-sensitive sandy soils and loess soils exceed the nitrate-N limit of 11.3 mg/L in the shallow groundwater, and that none of the farms on clay and peat soils exceeded this limit. Mean nitrate-N concentration in the groundwater of sandy soils was 8.8 mg/L and of loess soils 12.5 mg/L. Mean milk production of the 281 farms in 2012 was 15 700 kg/ha, mean utilised grass yield 10 800 kg/ha and mean silage maize yield 16 900 kg/ha. The amounts of N and P in purchased feedstuff was equivalent to 192 and 29 kg/ha, respectively. Mean fertiliser-N use was 125 kg/ha, mean manure-N use 241 kg/ha, mean fertiliser-P use 1.5 kg/ha, mean farm-gate N surplus 179 kg/ha and mean P surplus 4 kg/ha (RIVM 2014). Farms exported on average 34 kg of manure-N and 7 kg of manure-P from the farm, in order to comply with the N and P application limits. However, differences between farms are large.

In summary, grassland-based dairy farming is a productive and regulated sector in NL. The eco-efficiency of dairy production is one of the highest in the EU-27 (Lesschen *et al.* 2011). However, profitability is under pressure due to increasing cost of land, manure disposal and low-emission housing systems. There is also increasing debate about the consequences of the side-effects of imports of feedstuff from other countries (Bos *et al.* 2013; Lassaletta *et al.* 2014; Taube *et al.* 2014).

New Zealand

Grassland-based animal production is the backbone of the economy of New Zealand (NZ), and grazed pastures dominate the landscape. About one-quarter (6 Mha) of NZ's land area is high-yielding grassland, and another 30% is covered by grassland of low productivity (8 Mha). The high-yielding grasslands are typically ryegrass–white clover-based and are intensively grazed year-round by predominantly dairy cattle, sheep and beef cattle. The low-cost, clover-based systems and the temperate climate that enables cattle to graze year-round are the key factors in the competitiveness of the NZ dairy industry. The low-producing grasslands are grazed predominantly by sheep and beef cattle. The area of cropland is <0.5 Mha, and the area of forest and natural vegetation is ~12 Mha.

Livestock numbers have changed considerably; sheep numbers have more than halved since the early 1980s, and dairy cow numbers more than doubled (Fig. 6). Although sheep numbers halved between 1981 and 2009, sheep production reduced by less than a quarter, which reflects the significant increase in per-animal production over time. Similarly, beef production increased despite a reduction in beef cattle numbers. The largest increase in productivity has been in the dairy sector, with milk production almost tripling while animal numbers doubled. Also, the total area of land under dairying as well as cow numbers per ha increased (by 6.3% and 6.7%, respectively, between 2002 and 2009). All of these factors combined have resulted in an increase in milk output per area of land of 12% between 2002 and 2009. Mean production of milk solids (milk fat+ protein) increased from 600 kg per effective ha in 1990 to 800 kg in 2000 and 1000 kg in 2011 (New Zealand Dairy Statistics 2012). Hence, the 17 billion kg of milk delivered to the dairy-processing industry in 2010 is produced on dairy farms with a mean milk yield of 12 500 kg/ha.year, and with 3800 kg/cow.year.

The expansion and intensification of the dairy sector has increased concerns about the ensuing pressures on soil and water resources. As a result, there has been significant focus on research to develop management practices for minimising the environmental footprint of dairy farms (e.g. Monaghan *et al*. 2007; de Klein *et al*. 2010). One of these research initiatives was the Best Practice Dairying Catchments project, which was established in 2001 to integrate environmentally sustainable practices into dairy farming (Monaghan *et al*. 2008). In 2001, 2003, 2006 and 2009, detailed farm and land-management surveys were conducted in five catchment to gather information on farm productivity levels, fertiliser use, purchased feed, farm effluent, irrigation, and soil management practices. The results typically show significant increases in milk production, stocking rate and N losses per ha over time (Monaghan *et al*. 2008; de Klein and Monaghan 2011). Although N leaching and N_2O emissions per unit of milk produced decreased over time—indicating that the farms became more efficient—the rates of efficiency gain were lower than the rate of production increase. As a result, total N leaching and N_2O emissions increased significantly. Simulation studies indicate that increasing milk production from 14 500 to 19 100 kg/ha.year would double total N-leaching losses and increase total N_2O emissions by 45%, while N losses per unit of product would increase by 58 and 10%, respectively (de Klein and Monaghan 2011).

The adoption of emission-mitigation measures such as nitrification inhibitors, restricted grazing and low-protein supplementary feed can offset some, but not all, of the intensification-induced environmental losses (de Klein and Eckard 2008; Beukes *et al.* 2011; de Klein and Monaghan 2011). In addition, these options often come at a cost. The most cost-efficient way of achieving the dual goals of increased productivity and reduced environmental losses is to focus the management on practices that achieve 'more for less', that is, more milk per animal or per unit of dry matter intake, and more dry matter per unit of N input, rather than focusing on mitigation of N losses.

Discussion and synthesis

Forecasts indicate that global milk production will increase by 1.1% per year from 664 billion kg in 2005–07 to 1077 billion kg in 2050 (Alexandratos and Bruinsma 2012). Similarly, beef and mutton production will increase by 1.2 and 1.8% per year, respectively, from 64 and 13 billion kg in 2005–07 to 106 and 25 billion kg in 2050. Herbage and forage production will have to increase strongly to meet the increased feed demands of the increasing numbers of cattle and sheep in the world. Most of the increased demand will come from developing countries, especially in Asia, Africa and Latin America. Although domestic consumption of dairy and beef will likely show little increase in affluent countries, dairy-exporting countries such as NZ, NL and Chile see market opportunities in the increasingly globalised world, which contributes to a further intensification of grassland and forage use in these countries.

Does intensification of grassland and forage use lead to efficient, profitable and sustainable ecosystems? Our preliminary answer of 'yes, but not necessarily' in the *Introduction* was mostly substantiated by the country cases. The intensification of dairy production has brought economic prosperity but has also led to serious environmental issues and societal responses, which require adjustments in production methods. Grassland-based dairy farming and beef farming in all three countries are competitive sectors, which so far have managed to cope with changes in the biophysical, economical and societal environments during the last decades. These cases demonstrate the versatility and resilience of the dairy and beef sectors and of grassland and forage use. The sectors have responded and will have to respond rapidly in the future to the changing environment. The country cases also illustrate that there are biophysical, economic, environmental and societal limits to grassland and forage use, and that there is relatively large room to manoeuvre, to adjust the systems to the changing environments.

The aforementioned limits vary in degree and importance depending on region, markets, science and technology, management, society and time. Some of these limits are pliable through technical progress and management. Some limits, though, are critical, and overcoming them may lead to large shifts and transitions (Scheffer 2009). Figure 8 shows three examples of 'unsustainable' livestock farming systems that sooner or later may collapse because they exceed biophysical, environmental, economic and societal limits. Unsustainable systems have low income and/or high environmental impacts; sustainable systems have high income, high social acceptability, and acceptable environmental impact. Overstocked, low-productivity communal production systems are in a highly vulnerable situation; temporary droughts force them to move or quit. Unregulated feedlots face environmental and social acceptability challenges, and low-productivity and extensive production systems are outcompeted economically.

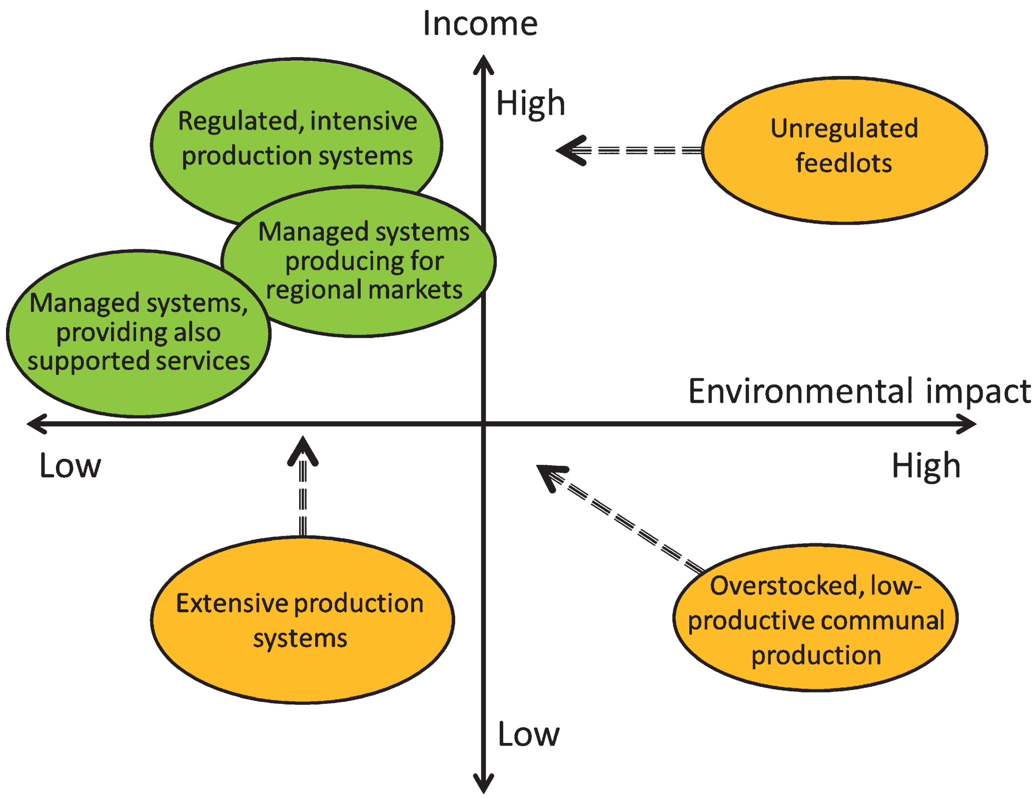

Fig. 8. Pathways to increase the sustainability of dairy and beef production. Unsustainable systems have either low income and/or high environmental impacts; sustainable systems have low environmental impact, high income and high social acceptability (after McDermott *et al*. 2010).

Both external driving forces (Fig. 1) and internal driving forces (the law of the optimum) provide incentives for intensification, i.e. for increasing the output per unit surface area and labour. Technological progress and systems changes provide opportunities to increase almost continuously the production per unit surface area and per unit labour (Figs 2–4). The three country cases (Fig. 6, Table 1) suggest that intensification is indeed a global phenomenon, constrained by biophysical, economic and societal limits, which are to some extent pliable and dynamic. The relevant question is: where, when, how and how far to intensify production while considering the critical limits. Unfortunately, there is no universally applicable recipe for sustainable intensification of grassland and forage use, because of the spatially diverse and dynamic biophysical, economic and societal environments.

The optimum level of intensification is a moving target. Intensification requires a farm-specific plan and farm-specific strategies, which need to be re-analysed and possibly adjusted to the changing environments. With regard to intensification, the requirements are talent, knowledge and training to compete and survive in the global 'rat-race', where low-cost producers determine bottom milk prices in a market with increasing price volatility. Intensification in a global market results in an increase in marketable output, a decrease in production costs, and cheaper food. High-cost producers will be squeezed out (Fig. 5) or will have to diversify production to provide high-value products for local markets or provide support services to society (Fig. 8). Farmers will have to strive for the minimum of each production resource that is needed to allow maximum utilisation of other resources at the farm. All production factors have to be in balance to assure high resource-use efficiency, and hence, high economic return on investments and low losses to the environment (de Wit 1992). This emphasises the importance of 'management', i.e. the allocation and handling of all resources at the right time, in the right amount, the right way and the right place. Intensification of grassland and forage use tends to increase GHG emissions and NO_3^- leaching per unit of surface area, but tends to decrease GHG emissions and NO_3^- leaching per unit of produce. Intensification increases the need for emission mitigation measures.

The country cases indicate that farmers have applied three broad strategies to increase milk production, but to variable degrees: more cows per ha, more milk per cow, and more land per farm. All three strategies have side-effects, which differ between countries. Upscaling (increasing herd size) and increasing stocking density have been the main strategies in NZ, whereas increasing milk yield per cow and upscaling have been the main strategies in NL. The percentage of intensive farms (milk yield >~15 000 kg/ha.year) is larger in NL than in Chile and NZ, but the rate of intensification is higher in Chile and NZ than in NL, mainly because intensification in NL started in the 1960s, but was halted by the introduction of the milk-quota systems in 1984 and by strict nutrient-management regulations from the 1990s. The dairy sector in Chile is in a rapid transition; the number of farms with <50 cows and especially with <10 cows is rapidly decreasing and the number of farms with >300 cows is increasing. Mean stocking density is still low (<1 dairy cow/ha) in Chile compared with NZ (mean 2.8 cows/ha) and NL (1.6 cows/ha) but is increasing because the potential for forage production is large. Farm studies indicate that current differences between farms are huge; farm size ranges from <10 to >1500 cows per farm, mean milk yield per cow from <3000 to >10 000 kg/cow.year, and mean milk yield per farm from <3000 to >25 000 kg/ha.year. However, certain combinations are less sustainable, because they are not economically viable, environmentally sound or socially acceptable, depending also on region (Fig. 9).

The country cases suggest that increasing the milk production beyond 10 000–15 000 kg/year is associated with increasing costs (economic and environmental) and societal concern. Increasing milk yield beyond 10 000–15 000 kg milk/ha.year requires supplemental feeding, depending on region. With the purchase of concentrate feeds, additional N and P and other nutrient elements are imported as well, and these are only partially exported with milk and beef again (Lassaletta *et al.* 2014; Taube *et al.* 2014). Most of the imported elements either accumulate in the soil (especially P, K, copper and zinc) or are lost to air and water (N, sulfur), unless precautionary mitigation measures are taken. Dairy farmers in NL with >12 000–15 000 kg milk/ha.year must export the surplus manure to other farms (or countries) and must take mitigation measures. Restricted and zero-grazing strategies are effective to increase the utilisation of herbage and forage, increase milk yield per cow, and decrease NO_3^- leaching losses. However, NH_3 emissions increase and therefore require expensive, low-emissions housing systems. Dairy farmers in NZ with > ~15 000 kg milk/ha.year face high NO_3^- leaching and N_2O emissions, depending on N management. Nitrogen losses can be mitigated through nitrification inhibitors and guided grazing, which tend to increase the cost of milk production (Beukes *et al.* 2011; de Klein and Monaghan 2011). In addition, the required knowledge, management skill and energy cost increase.

Although large, high-technology stables and 'agro-production parks' are technically and economically efficient (e.g. Smeets 2009), public opinion in NL is heavily against these so-called mega-stables, especially near villages and urban areas, because of possible issues related to odour, noise, landscape, animal welfare, and zoonosis (Breeman *et al.* 2013). Mega-stables are not well defined, but in the public perception have > ~300 dairy cows, or an equivalent number of goat, pigs and chicken, and are nearly landless (zero-grazing). The public aversion to high-technology, zero-grazing mega-stables in NL illustrates the importance of societal limits to high-technology intensification of grassland and forage use, as well as the need for public debate about 'sustainable intensification'.

There are winners and losers in the rat-race of intensification (Figs 5 and 8). The winners are farmers who are able to achieve a high return on investments and thereby out-compete farmers with a low return on investment, and at the same time have built trust in society. Losers are small farmers who drop out of business everywhere in the world, and the environment. Losers can be also large, intensive farms, when animal welfare, animal health and environmental quality are at stake, and social uproar creates a feeling of alienation between the farming community and the rest of the society (Bos *et al.* 2013; Breeman *et al.* 2013). Small farmers tend to stay in business as long as possible by minimising costs and, in some cases, by broadening the income base through providing services to other farmers and other people. Supporting rural development and so-called 'green services' through direct support (payments) is a main vehicle in the European Union for landscape maintenance and rural livelihood, and indirectly also for small producers to stay in business (e.g. Van der Ploeg 2009).

The environment, that is, air, water, and natural ecosystems, is often also a 'loser' in intensification, though not necessarily, as all three country cases illustrate. The relationship between intensification of grassland and forage use and its environmental impact is complex, as it is influenced by site-specific conditions, the type of system and the management. Intensification of grassland and forage use often leads to increased emissions of N, P, CH_4 and N_2O per unit surface area and to decreased emissions per unit of produce. The rates of increase per unit surface area, and of the decrease per unit produce, greatly depend on the system and the management. Hence, optimal ranges of intensification of grassland and forage use can be defined (Fig. 9) with minimal emissions per unit of surface area and per unit of produce. These ranges depend on site-specific conditions, system and management, and on societal demands. At the same time, investments must be made in building relationships with, and trust in, the local society (Breeman *et al.* 2013; Scholten *et al.* 2013). Environmental limits may be met through a range of measures, including (*i*) increases in productivity through breeding and selection, (*ii*) low-protein and low P-feeding strategies, (*iii*) low-emissions housing systems and techniques

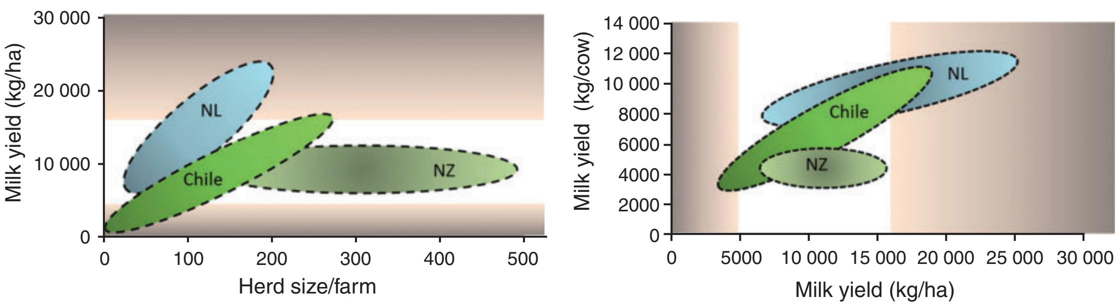

Fig. 9. Relationships between herd size and milk yield per ha (left panel) and between milk yield per ha and milk yield per cow (right panel) on current dairy farms in Chile, The Netherlands and New Zealand.

for manure storage and application, (*iv*) drastic decreases in fertiliser use, (*v*) knowledge-driven grassland and forage use and management, (*vi*) export of animal manure, and (*vii*) outsourcing of specific farm activities (e.g. raising young stock). Smart combinations of these measures and techniques provide additional room for manoeuvre during intensification.

Conclusion

Intensification of grassland and forage use is a global phenomenon in response to farm internal and external driving forces. The optimum level of intensification is a moving target, because of the changing biophysical, economic and societal environments. There are three broad strategies, and intensification of grassland and forage use in practice is multi-faceted. Relationships between intensification, farm income, and environmental and societal impacts are complex, because of site-specific bio-physical, ecological and societal constraints. Intensification results in winners and losers. The environment can be a 'loser', unless mitigation measures are taken to decrease the environmental impacts.

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