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A method for assessing sustainability, with beef production as an example

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ABSTRACT

A comprehensive approach to decisions about the use of land and other world resources, taking full account of biological and other scientific information, is crucial for good decisions to be made now and in future. The sustainability of systems for producing food and other products is sometimes assessed using too narrow a range of component factors. A production system might be unsustainable because of adverse effects on a wide range of aspects of human welfare, animal welfare, or the environment. All factors should be included in sustainability evaluation, otherwise products or actions might be avoided without adequate consideration of key factors or of the diversity of production systems. A scoring method that is based on scientific information and potentially of general relevance is presented here, using beef production as a example with a review of each of its sustainability components. This includes an overall combined score and specific factors that make the system unacceptable for some consumers. The results show that, in this example, the sustainability of the best systems is very much better than that of the worst systems. By taking account of scores for a wide range of components of sustainability in comparing beef-production systems, better quality policies about beef use can be formulated than when statements referring only to one system are considered. The least sustainable beef-production systems are extensive grazing that causes land degradation and the use of feedlots or indoor housing with grain feeding. Semi-intensive silvopastoral systems are the most sustainable beef-production systems, and well-managed pasture-fed beef from areas where crop production is uneconomic is also sustainable. This simple, scientifically based scoring system could be modified to use positive as well as negative scores and is of value for policy makers, researchers, producers, organisations aiming to improve sustainability, and the general public.

Key words: sustainability assessment, land and water usage, biodiversity, animal welfare, greenhouse gas, human-edible feed, beef production, feedlot, forage-based systems, silvopastoral

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I. INTRODUCTION

A key question in relation to any human action is whether or not it is sustainable. The sustainability of human management of land is a key biological issue because human actions are a part of biology, not something separate from it, and the survival of many organisms is affected by the agricultural systems that are used. Many studies of sustainability consider one or a small number of its components (Smith *et al.*, 2013) and statements are based on evidence concerning only certain aspects of sustainability. For example, when considering only greenhouse gas production, pig and poultry meat may appear more sustainable than meat derived from pasture feeding or all red meat may be considered equally unsustainable (Steinfeld *et al.*, 2006; Clonan *et al.*, 2015; Siegrist & Hartmann, 2019), but neither is true when all components are considered. Failure to consider all components of sustainability can thus affect whether effective and fair decisions are taken. In this review, after discussing the concept of sustainability, a simple but comprehensive sustainability assessment system is presented. Other attempts to produce a composite index of sustainability were reviewed by Singh *et al.* (2009), who advocated careful determination of the range of measures needed. Sustainability evaluation and decision criteria have been reviewed previously by Gibson, Hassan & Tansey (2013) and Sala, Ciuffo & Nijkamp (2015).

The meaning of the term 'sustainable' is now much wider than in the past (Herrero *et al.*, 2012; Broom, 2017*a*,*b*). Systems have been called unsustainable when there was no market for a product, when a resource became depleted such that it became unavailable to a system, or when a product of a system accumulated to a degree that prevented system functioning. Currently, a system can be unsustainable because of one or more of a wide range of negative impacts. A system or procedure is sustainable if it is acceptable now and if its expected future effects are acceptable, in particular in relation to resource availability, consequences of functioning, and morality of action (Broom, 2014). Judgements by government and other agencies, and by the general public, of what is acceptable will be ethical evaluations of available information, ideally information of good scientific quality (Bañon Gomis *et al.*, 2011).

Factors that might make a food-production system unsustainable, discussed in detail here in relation to beef production, include: adverse effects on human welfare, including health; poor welfare of production animals; inefficient usage of world resources; harmful environmental effects, such as greenhouse gas production, water pollution including by nitrogen and phosphorus, low biodiversity or insufficient conservation; reduced carbon sequestration; unacceptable genetic modification; not being 'fair trade', in that producers in poor countries are not properly rewarded; insufficient job satisfaction for those working in the industry; and damage to rural communities (Broom, 2017*b*). Decisions about the sustainability of any product, system or action will depend on trade-offs among the components and comparisons will usually result in a hierarchy where there are alternatives (Marshall & Toffel, 2005; Pope *et al.*, 2017).

The components of sustainability are now thought of as an aspect of product quality that alters purchasing habits and hence causes changes in production methods (Broom, 2010, 2014) but individuals vary in their priorities. For example, low-quality products for some consumers include palm oil or soya products because of negative environmental impacts of production methods, and some animal products because of poor welfare of the production animals. The economy of societies has been changing and there is now more of a 'pull society' driven by consumers and less of a 'push society' driven by producers (Broom, 2014, 2017*a*) with the demand pull being more detailed in its requirements than sometimes assumed by economists (e.g. Kim & Lee, 2009; Antonelli & Gehringer, 2015).

After discussion of sustainability assessment methods, a comprehensive analysis method with a decision-making system is presented herein. To illustrate this, an analysis of an example of a production system is used: beef production, which has often been considered unsustainable. However, sustainability evaluations of beef production tend to be limited to feedlot systems and inefficient extensive systems. In order to provide evidence upon which to base future decisions about the best use of land, beef-production systems are compared and evaluated taking account of a wide range of sustainability factors. Sustainability component scores are evaluated, analysed and discussed in relation to beef production and to future food production more generally.

II. DECISION-MAKING ABOUT PRODUCT SUSTAINABILITY

Each of the components of sustainability listed above and used in the analysis involves assumptions about an 'ideal' situation. It is assumed that harms to the welfare of humans and other animals, to the world environment and to world and local biodiversity should be minimised. Some seek to return land areas to a natural environment, as is required by law for 20% or more of farmed land in Brazil, but the concept of 'natural' is often loosely defined. For example, bare hilltops in temperate countries may be thought of as natural but many are a consequence of historical grazing by animals managed by humans. Biodiversity evaluation has become more sophisticated (Heywood & Watson, 1995; Gontier, Balfors & Mörtberg, 2006; Callaghan *et al*., 2019) and it is clear that biodiversity can be greater in modified environments than in some habitats unmodified by humans. The concept of the 'ideal' for each sustainability component can also change over time.

The use of land is often decided by farmers and local managers on the basis of short-term commercial expediency, with products and methodologies subsequently modified according to the degree of economic success. For any product, knowledge about past production success has much influence on the methodology used but there is increasing consideration of consumer demands, and hence, to some extent, sustainability. Local conditions, such as temperature range and water availability, will affect agricultural production success in any given location. However, there are systems that can be used with some modification in many parts of the world.

Governments and international agencies considering sustainability can limit negative actions by laws, or can promote positive actions such as the use of better systems. In order to achieve either of these they need a wide-ranging evaluation of sustainability. The public, producers and scientists also need this. However, since the components of sustainability are diverse, there is no single scientific unit that encompasses them all. It is not correct to use only one component of sustainability as if it represented all components. Attempts to find a single unit, for example by representing each component in monetary terms or in energy terms, are not valid. Many of the harms to the world that are now being considered unsustainable actions have occurred because the option used was that with the lowest cost or that which made the most profit for the producer. For example, very high stocking densities of animals and close confinement in small cages reduce production costs but cause poor welfare. Widespread use of certain pesticides appeared to be economically viable but has had negative impacts on humans and wildlife. Using slave labour or paying poor farmers a very low price for products such as cocoa and coffee initially increased profits but has led to changes in law, the introduction of fair trade schemes and harms to individual and company reputations. In some situations, reducing energy use increases sustainability but in others, reducing human effort, distance travelled or duration of action do not. For example, using more pesticide, herbicide or prophylactic antibiotics may reduce energy usage but cause various harms. Travelling to check individual animals may use more energy but prevent poor welfare by allowing treatment of injury or disease. Planting trees has some energy costs but may lead to a range of benefits.

One solution is to produce a score for each component of sustainability using the best available science concerning that component. The scores, on an arbitrary scale but based on objective, published, scientific assessments for the components, can then be combined. It would be possible to use both positive and negative scores but most current analyses consider negatives so that is done in the example presented here. The assessments for each component indicate in a quantitative way the range from zero negative effect to what is regarded as most negative by scientists studying that component. In the example used here, the most negative is scored −5 and negative effects are placed on the scale from −1 to −5. Those scoring should attempt to score in an equivalent way for all components by using the knowledge of specialists in each. Provided that −5 is equally negative for each component, the other scores will also be equivalent. The measures of some components are numerical values but these still have to be interpreted. For a measure such as water use, numerical values for the actual amount of water used can be calculated and used but the scoring decided upon may be different according to the likelihood of water shortage in a region. Hence comparisons of systems could be made for a particular region, or for the whole world as in the example used here. The scope should be made clear. Although there may be some variation in what is considered most negative amongst scientists who are experts on the different components, the advantage of being able to obtain an overall sustainability score justifies use of the scoring system.

This scoring system makes it possible and rational for those making ethical decisions about sustainability to allow components to compensate for one another. For example, a slightly higher increase in greenhouse gas output in one system may be accepted if the efficiency of resource use or animal welfare is better in that system. However, not all decisions are made using such consequentialist ethics in which various costs and benefits are balanced. Some ethical decisions are based on deontological arguments, using which a production system may be unacceptable, and hence unsustainable, because consumers consider one of its actions or consequences always to be wrong. For example, because of scientific evidence for poor welfare of veal calves kept in small crates, some consumers will never buy a product from that system. A second example is of consumers avoiding purchasing beef produced on farms in areas where pristine rainforest was felled, because they believed that such production was morally unacceptable. Consumer pressure resulting from this resulted in financial harm to the large commercial companies producing or marketing that beef and led to policy change in both companies and countries.

The review of sustainability components in the beef-production example used below follows the order listed in Section I. For each component, the scientific evidence for the scores is discussed, with an explanation of the score allocated in Table 1 for each beef-production system.

III. ASSESSMENT OF SUSTAINABILITY COMPONENTS FOR BEEF PRODUCTION

Methodologies such as life-cycle analysis (e.g. Ciambrone, 2018) and measurement of system externalities (Balmford,

Table 1. Sustainability components and score for beef-production systems. Numbers indicate negative scores; zero-tolerance (Z) for some consumers is indicated where appropriate. Genetic modification, fair trade and rural community components do not score as negatively as −1 for any of the systems so are not included in this table

Beef-production systems	Sustainability components									Total scores
	Human health	Animal welfare	World resources			Greenhouse gas production	Water pollution; N/P cycle disruption	Biodiversity	Carbon sequestration	
			Land usage	Land area	Water used					
Extensive pasture degraded (1A)	−1	−3	−3	−5, Z	−1	−5, Z	0	−4	−4	**−26, ZZ**
Extensive pasture not degraded (1B)	−1	0	0	−3	−1	−3	0	−2	−2	**−12**
Fertilised irrigated pasture + concentrates (2A)	−1	0	−4	−3	−4	−2	−2	−4	−3	**−23**
Fertilised irrigated pasture no concentrates (2B)	−1	0	−2	−2	−3	−2	−1	−3	−2	**−16**
Fertilised irrigated pasture to feedlot (3A)	−2	−2, Z	−4	−2	−4	−1	−2	−4	−4	**−25, Z**
Extensive pasture to feedlot (3B)	−2	−2, Z	−2	−4	−4	−2	−2	−3	−4	**−25, Z**
Fertilised irrigated pasture to indoor (4A)	−2	−3, Z	−4	−2	−4	−1	−2	−4	−4	**−26, Z**
Extensive pasture to indoor (4B)	−2	−3, Z	−2	−4	−4	−3	−2	−3	−3	**−26, Z**
Indoor rearing to indoor (4C)	−2	−4, Z	−4	−3	−4	−1	−3	−4	−4	**−29, Z**
Semi-intensive silvopastoral (5)	−1	0	0	−1	0	−1	0	−1	−1	**−5**
Dairy-origin calves	−2	−2, Z	−3	−2	−4	−1	−2	−3	−3	**−22, Z**
Beef-origin calves	−1	−1	−3	−3	−3	−2	−2	−2	−3	**−20**

Green & Phalan, 2012; Balmford *et al.*, 2018) can be used to assess sustainability. A recent life-cycle analysis for beef production (de Vries, van Middelaar & de Boer, 2015) considered some environmental aspects of sustainability but additional components are included in the present study, for example animal welfare, loss of biodiversity, water usage and aspects of human welfare. A key point in relation to beef sustainability, as de Vries *et al.* (2015) point out, is that life-cycle analysis methodology does not consider the extent to which land used for beef production could be used for other human food production. Global sustainability decisions should also take account of regional differences in productivity. Tree production for example, either with or without beef from agroforestry (Soler *et al.*, 2018), is more efficient in sub-tropical than in temperate conditions. The present analysis of the sustainability of beef-production systems refers to the whole world but regional analyses of what is practicable could also be affected by global variation in light reflectance and hence views about the desirability of pasture usage in temperate and tropical situations.

Table 1 shows a zero score or a negative score from −1 to −5 for each sustainability component based on reviewing the scientific evidence for that component. Where there is evidence (from surveys such as Eurobarometer) that 10% or more of all potential consumers are zero-tolerant, finding beef completely unacceptable because of that component, 'Z' is shown.

(1) Beef-production systems

The systems for beef production considered herein are widely used on commercially successful farms. Although some beef consumed is from sources local to the consumer, much is transported over large distances. Beef might come from temperate, tropical or sub-tropical sources. The transport of the product is a factor affecting sustainability but does not vary with system so is not considered in this comparison.

Fig 1. Example of cattle kept in a semi-intensive silvopastoral system with *Leucaena leucocephala*. Photograph, C. Cuartas.

The breeds of cattle used in the various systems are selected by producers according to factors such as growth rate in local conditions, ability to adapt to expected environmental temperatures and vulnerability to pathology, for example tick-borne diseases. In comparing systems for sustainability of producing beef, it is assumed that appropriate breeds were used for all data investigated, and no attempt is made to categorise according to breed.

The focus herein is on beef production but much beef comes from animals also used for dairy production (Lowe & Gereffi, 2009). The origin of calves used in beef production, from the dairy industry or from suckler herds or other beef breed production, was an important variable affecting aspects of sustainability in the analysis of de Vries *et al.* (2015). The systems compared here are those for beef production, but the sustainability of calves from dairy origin and those from beef-farming origin are compared in Table 1. Another important variable is whether or not the system complies with organic standards, but there is some difficulty in making such comparisons from the literature due to the great variation in both organic and non-organic systems. Similar problems apply to comparisons of high-roughage and low-roughage systems. For example, roughage effects on greenhouse gas production differ depending on whether the feed is conserved forage or fresh plants grazed or browsed from a variety of species, and whether the fresh or conserved feed is from high-nutrient or low-nutrient sources (Mogensen *et al.*, 2015). Neither organic standard nor level of roughage is specified in the comparison of systems here.

The first system considered here (1A,B in Table 1) is the extensive unmodified pasture system used in temperate, tropical, upland and lowland areas. This involves rearing the cattle throughout their lives on pasture, initially with their mothers and then in age-related groups and is largely equivalent to the 'extensive grazing management' system of Allen *et al.* (2011). 'Unmodified' does not mean that livestock do not alter the pasture but is emphasised to distinguish this system from fertilised pasture and silvopastoral systems that are also extensive. The manure from the animals is usually left on the land. No artificial fertiliser is used and the land is not irrigated. There are great differences in sustainability between systems where pasture and soil become degraded and those where the pasture recovers fully and rapidly after a period with cattle on it. Davidson *et al.* (2008) distinguish photosynthetic plant cover, non-photosynthetic plant cover and exposed soil. For this analysis, where degraded (1A) and not degraded (1B) systems are considered separately in Table 1, degraded means that more than half of what would normally be pasture with photosynthetic cover is exposed soil or non-photosynthetic.

A second system is fertilised pasture, irrigated when necessary (2A,B). Systems where additional concentrate feed is used (2A) are distinguished in Table 1 from those where it is not used (2B). Supplementary pasture-derived or concentrate food is used in systems where pasture growth is insufficient to feed the animals during a dry period or during the cold seasons in temperate areas.

The third and fourth systems involve animals that undergo their final growth period in feedlots (3A,B) or inside buildings (4A–C) where they are usually housed on slatted floors. When young, the cattle are often kept on fertilised, irrigated pasture and then transported to feedlots (3A) or indoor housing (4A) where they are fed high levels of concentrates for the last few months of life. Other animals are kept extensively prior to the feedlot (3B) or indoor fattening (4B) period, and some are housed throughout life (4C).

A fifth system, increasingly used in tropical and subtropical countries throughout the life of the cattle, is the semi-intensive silvopastoral system (5) (example in Fig. 1) that utilises, in addition to pasture plants, shrubs with edible leaves such as the high-protein leguminous shrub *Leucaena leucocephala*, together with trees which may also have edible leaves (Murgueitio, Cuartas & Naranjo, 2008; Ku Vera *et al*., 2011; Broom, Galindo & Murgueitio, 2013; Murgueitio *et al*., 2015). The trees have a role in providing shade whilst those with edible leaves are valuable in times of low rainfall. The highly palatable leaves of these shrubs and trees necessitate the use of rotational management where the cattle are moved from paddock to paddock before they damage the plants. There can be more animals per unit land area for a given growth rate than on pasture-only systems. Semi-intensive silvopastoral systems are used in thousands of farms in Colombia, Mexico and Brazil, and increasingly in Argentina, Australia and other countries. Some are in temperate regions or at altitude in subtropical countries (Peri, Dube & Varella, 2016; Pachas *et al*., 2018; Radrizzani *et al*., 2019). The term 'intensive silvopastoral' is not used here as the system is not intensive farming *per se*; the term 'semi-intensive' reflects the higher density of animals than in pasture-only systems. Silvopastoral systems that do not use shrubs or trees as forage are not considered here but some may be productive enough to warrant detailed comparison in the future.

(2) Effects on human health

Health is a key aspect of human welfare and is a major factor affecting purchasing by consumers. Other aspects of human welfare are considered below as different components of sustainability. Consumption of beef has a positive effect on human health, providing essential nutrients, although these nutrients are also available from other sources. Human health, including cancer incidence, can be worse when large amounts of beef are consumed (Cross *et al*., 2007) and, particularly for processed meat, the risk of colorectal cancer increases (Boada, Henríquez-Hernández & Luzardo, 2016). A high intake of beef could involve levels of saturated fat intake that would predispose some individuals to heart disease. However, if beef intake is moderate, and not associated with obesity, there is no increased risk of heart disease (Wagemakers *et al*., 2009) and little overall effect on health. Beef from different production systems can vary slightly in nutrient quality. Forage-based systems improve fatty acid profiles of meat in comparison with concentrate-based systems. The *n*-3 series polyunsaturated fatty acids (PUFAs) that are recommended by nutritionists for the human diet are at higher concentrations in beef from forage-fed cattle than from grain-fed cattle (Nuernberg *et al*., 2005; Warren *et al*., 2008; Daley *et al*., 2010).

The development of antimicrobial resistance (AMR) is one of the greatest current threats to human health (Broom, 2020). AMR leads to higher mortality from previously treatable bacterial diseases such as tuberculosis, which kills two thirds as many people every year as the SARS-CoV-2 virus killed in 2020. AMR has occurred partly because of misuse of antibiotics in human medicine, especially in countries that do not control their sales, use and disposal, but also partly as a result of widespread (rather than therapeutic) use in livestock farming (Ungemach, Müller-Bahrdt & Abraham, 2006). Beef-production systems with high densities of animals, in particular cattle housed on slatted floors and in feedlots, are more vulnerable to disease and hence more antibiotics are used in these systems (Sneeringer *et al*., 2015). The disposal system for urine and faeces from these systems may also promote the development of antimicrobial-resistant pathogens. Dairy systems use more antibiotics than beef systems (Hommerich *et al*., 2019). If well managed, each of the more extensive systems poses less risk for the development of AMR.

In Table 1, the human health component score is −1 for all beef, to reflect the consequences of excessive consumption. Systems that are more likely to lead to AMR, because of high stocking densities and consequent antibiotic use (3A, 3B, 4A, 4B, 4C), have a score of −2.

(3) Welfare of production animals

For many people, the welfare of animals is the most important component of sustainability. Eurobarometer (2007) found that 34% of consumers stated that animal welfare was their most important concern about farm animals and their products, 43% said that they buy welfare friendly products and only 2% said that animal welfare is unimportant. Information availability facilitates translation of preferences into actions (Toma *et al*., 2012). More recently, 95% of a large sample of EU citizens said that farm animal welfare is important to them (EU D.G. Health and Food Safety, 2016). Cattle have a high level of cognitive ability and emotional responsiveness, and cattle welfare can be scientifically assessed using a wide range of measures (Kilgour, 1987; Hagen & Broom, 2004; Broom, 2014). Cattle (*Bos taurus* and *Bos indicus*) originally lived in forest, forest-edge and river-edge areas (Köhler, 1993; Hall, 2008). Despite experience of pasture rearing, modern cattle often browse, utilise a wide range of wooded areas and select areas with shrubs and trees rather than open areas (Roath & Krueger, 1982). Some extensive pasture systems and all silvopastoral systems provide these resources.

Poor welfare in many beef cattle can arise from disease when introduced to the fattening system. Young cattle are transported to feedlots, or other large-group systems, and are then mixed with many other individuals and offered food using a feeding system to which they are not accustomed. A serious welfare issue is that many then develop diseases such as bovine respiratory disease (Kelly & Janzen, 1986; Duff & Galyean, 2007) or bovine viral diarrhoea (Campbell, 2004). Transport is stressful and lowers immune system responses to pathogens. Mixing of calves exposes them to new pathogens and the stress involved with adapting to novel food and a novel feeding system (Broom & Fraser, 2015). Much disease in beef cattle is not system-related, but these early disease problems, and hence welfare, are worse in most feedlot and indoor rearing systems (Schneider *et al.*, 2009; Magrin *et al.*, 2018). The welfare of calves of dairy origin is worse than those with beef cattle parents because they are taken from the mother at an earlier age (Webster, 2019). The welfare of dairy cow mothers is often much worse than that of beef cow mothers due to an association of lameness, mastitis and reproductive disorders with high levels of milk production (Oltenacu & Broom, 2010; Ahola *et al.*, 2011). In semi-intensive silvopastoral systems, compared with other pasture systems, the presence of predators of ticks and flies reduces transmission of diseases carried by these vectors to the cattle (Murgueitio & Giraldo, 2009).

Beef cattle have a strong preference for lying on straw or other bedding, rather than on a slatted floor, and low space allowance per individual leads to more aggression, injury and bruising (EU SCAHAW, 2001; Hickey, Earley & Fisher, 2003; Broom & Fraser, 2015). Cattle housed indoors on concrete or slatted floors often have pain from swollen hocks, swollen knee joints or other leg injuries that is alleviated by analgesics (Wagner, 2016; Wagner *et al.*, 2017). If there is an earth floor or bedding, these injuries are much less frequent (Grandin, 2016). However, among the fastest growing animals, for example those in many feedlots, joint and other problems mean that the legs are barely adequate to support the body. The consequence of this is cartilage damage, clear indications of limb pain and obvious difficulties in standing and lying (Dämmrich, 1987).

As indicated by preference studies, absence of pasture in feedlots and in long-term housed cattle results in poorer welfare. Cattle will walk to access high energy food but otherwise prefer to spend time on pasture, readily walking 240 m or more in preference to staying in a confined space (Spörndly & Wredle, 2004; Legrand, von Keyserlingk & Weary, 2009; Charlton *et al.*, 2011, 2012; Lee *et al.*, 2013). Cattle kept outside can also encounter difficult conditions that cause poor welfare, but poor welfare issues are more frequent in long-term housing production systems that do not meet their needs in multiple ways. Grandin (2016) reports that cattle in outdoor feedlots are often very muddy, especially at space allowances of less than 50 m^2 per animal, and the mud increases their food-intake requirement. In dry conditions, feedlots can have high dust levels that increase the risk of respiratory disorders.

Heat stress is a major welfare problem in most countries where beef is produced and direct sunlight can cause sunburn or increased susceptibility to certain toxins (Rowe, 1989). Heat stress, indicated by panting in cattle (Gaughan *et al.*, 2008; Gaughan & Mader, 2014; Mader & Griffin, 2015), is a substantial problem in feedlots, with deaths 24 times higher if shade is not provided (Busby & Loy, 1997). Fighting and mounting are welfare problems in feedlot cattle exacerbated by heat stress and lack of shade (Mitlohner, Galyean & McGlone, 2002). Welfare is better in semi-intensive silvopastoral systems because trees provide shade and the cattle can choose to be shaded or partly concealed. In these systems there is less fear and social interactions are more normal (Mancera & Galindo, 2011; Améndola *et al.*, 2013, 2016; Broom *et al.*, 2013).

The diet of cattle kept in feedlots is almost always more than 50% concentrate feed, the consequences of which can be painful acidosis, liver abscess and laminitis (Nagaraja & Lechtenberg, 2007*a*,*b*; Tucker *et al.*, 2015). Many feedlots lack roughage which can sometimes lead to eating earth. However, the high stocking density typical of indoor housing and feedlots, where economic returns are worse at densities less than 24 m^2 per animal (Montelli *et al.*, 2019), can result in poor welfare. Welfare is better if cattle can choose when to eat and what food to eat (Manteca *et al.*, 2008), as they do in extensive pasture and in semi-intensive silvopastoral systems (Broom *et al.*, 2013; Broom, 2017*b*). This improvement is partly due to better immune system function and reduced likelihood of disease (Broom, 2006). The welfare of cattle kept on extensive grazing systems can be very poor if there is insufficient food, an inadequate food balance, or insufficient water. Nutritionally deprived and water-deprived animals also are more susceptible to disease. Cattle spread over a wide area may not be checked with sufficient frequency, and so may lack food or water or have untreated diseases or injury.

When evaluating the score for welfare of beef cattle in different systems in Table 1, the worst score can be given to badly managed systems, such as extensive systems with insufficient food, water and poor husbandry leading to periods of starvation and disease (Phillips, 2008; Jank *et al.*, 2014). Hence there is a score of −3 for degraded pasture (1A). Where the systems are better managed, welfare is likely to be worst in cattle housed at high density and in feedlot cattle than in cattle maintained on pasture, with longer periods away from pasture correlating with a higher negative score [−2 for confinement in feedlots (3A,B) and −3 for indoor slatted-floor housing (4A,B); −4 for cattle kept indoors throughout their lives (4C)]. The best welfare (scoring zero) is for cattle kept on semi-intensive silvopastoral systems and in undegraded or irrigated pastures (Broom *et al.*, 2013). For some consumers, the welfare of cattle kept in feedlots or on slatted floors in buildings is so poor that these systems are never acceptable, especially if there was heat stress (Cardoso *et al.*, 2018) and they would not buy the product (Z in Table 1). Z is also marked for dairy-origin calves because some consumers find unacceptable the separation of the calf from the mother at birth, killing male calves at birth, treating low-value male calves badly, or failing to provide living conditions that meet the needs of dairy calves (Busch *et al.*, 2017). However, the dairy calves considered here are not treated like veal calves, or like calves kept for the dairy industry, but as calves for beef production. For welfare, the beef-origin calves are scored −1, this being the mean of the most frequent later conditions: extensive not degraded (0), fertilised pasture (0) and feedlot (−2). Dairy-origin calves have the score −2 because of earlier maternal deprivation and, for many, indoor-rearing conditions in the earliest part of life but the same mean for later in life.

(4) Efficiency of use of world resources: land usage

For high levels of sustainability in food production, resources such as energy, water and soil nutrients should be used, reused and recycled effectively (Jurgilevich *et al.*, 2016; de Boer & van Ittersum, 2018). Carnivorous animals, such as trout and salmon that are largely fed on other fish, provide an example of an unsustainable system unless their diet is composed of materials that people cannot eat or that would otherwise be wasted. Human food that might otherwise be wasted by food producers, food retailers, restaurants or domestic houses should be made available to people if possible and, if not, it can be treated to prevent disease spread and then fed to animals such as pigs (Zu Ermgassen *et al.*, 2016). Beef cattle can also be fed some human food-waste materials.

When considering the efficiency of land usage, the potential for land-use change should be considered (Nguyen, Hermansen & Mogensen, 2010). Much plant-derived food that humans could eat is fed to animals that then will be eaten by people, hence a proportion of the energy contained within the plant food is effectively wasted compared with direct consumption by humans. Where such food could not be eaten by humans, or would not normally be chosen as human food, the land where it was produced could sometimes instead be used for human food production (Herrero *et al.*, 2010). All beef production is subject to this very important criticism when the land used for production of cattle food could instead produce human food. However, herbivores such as cattle that eat forage plants (but not cereals) are an important component in relation to world resources compared with pigs or poultry, which compete with humans for food (Broom *et al.*, 2013; de Vries *et al.*, 2015; Broom, 2017*b*, 2018*b*). The assessment of the efficiency of human food production should thus take account of the proportions of human-edible and human-non-edible livestock feed components, including crop residues and food industry by-products (Wilkinson, 2011). Feed conversion by cattle and sheep is often said to be less efficient than that by pigs and poultry (Gerber *et al.*, 2015) but globally, ruminants use 5.9 kg of human-edible feed/kg of protein output whereas monogastrics need 15.8 kg/kg (Mottet *et al.*, 2017). As a consequence of the potential to grow human food on land instead of cattle feed, beef produced without grain-feeding uses world resources more efficiently than if grain is fed, hence grain-feeding systems, such as feedlots, are much less efficient. In cattle feedlots 44.3 kg of human-edible feed was used per kg of protein output in OECD countries and 37.1 kg in non-OECD countries. For meat production, these figures translate to a requirement for ruminants which are fed the world average amount of supplementary feed of 2.8 kg human-edible feed per kg boneless meat. Meat production from intensively kept pigs and broiler chickens is 3.5–4.0 kg human-edible feed per kg boneless meat, i.e. a worse value than ruminants except for grain-fed cattle from feedlot systems which require 9 kg human-edible feed per kg boneless meat (Mottet *et al.*, 2017). Where cattle are kept extensively for part of the year but moved to indoor housing in the cold or dry season, it is generally better to feed conserved herbage than grain during the cold or dry season. Cattle in temperate and sub-tropical Colombia on semi-intensive silvopastoral systems containing pasture plus leaves of high-protein shrubs or trees are 1.5–4 times more productive per unit of land used than cattle fed on fertilised pasture only so no supplementary feed is required (Murgueitio *et al.*, 2008; Broom *et al.*, 2013). Productivity similar to that of the semi-intensive silvopastoral system in Colombia is reported from lowland permanent pasture in temperate conditions (Orr *et al.*, 2019).

For efficiency of land usage, degraded extensive pasture (1A) is given a score of −3 in Table 1. Because much of the land used for extensive pasture that is not degraded (1B) could not be used for other human food production, for reasons such as unsuitable soil, mountain conditions and likelihood of flooding or of drought (Halder, 2013), the efficiency of usage is high and no negative score is given. Semi-intensive silvopastoral systems (5) use land very efficiently so they too are given no negative score. Where the pasture area could be used for producing plants for human consumption, a negative score is applicable: fertilised irrigated pasture (2B) is given a score of −2. Where concentrates such as maize and soya are fed to cattle, the score ranges from −2 to −4 depending on the duration of the period of concentrate feeding and the amount of concentrates fed (Wilkinson, 2011).

(5) Efficiency of use of world resources: land area

Land not used for agriculture could be used for conservation purposes (see Section III.9). In a comparison of the land area required for four different beef-production systems, including the land occupied by the animals, land to produce their feed and land to process meat, one tonne of beef required: 27 ha for extensive unmodified pasture, 20.7 ha for feedlots with pre-feedlot extensive conditions, 8.9 ha for feedlots with pre-feedlot irrigated pasture conditions, 10.0 ha for fertilised irrigated pasture, and 2.2 ha for semi-intensive silvopastoral systems (Broom, 2019*b*). Within each system there will be variation in the land area used, especially in extensive pasture systems, but the comparison of systems detailed above should be widely applicable. Nguyen *et al.* (2010) compared extensive or semi-extensive suckler beef calves and dairy bull calves in the EU, and calculated values of 17 ha per tonne for the most efficient dairy bull system and 43 ha per tonne for the suckler beef system. In other calculations for beef production (de Vries & de Boer, 2010; de Vries *et al.*, 2015), calves from dairy cows required a land area that was 53% of that for suckler calves from beef-breed parents because of land allocated to dairy production.

When final fattening takes place inside a building, the space occupied is only 2–3 m^2 per animal rather than 7 m^2 per animal in the feedlot calculation, but this is a minimal difference in comparison with the total if the early diet is the same: around 1% less than for feedlots. When the early rearing is also indoors, the diet normally includes a higher proportion of concentrates so the total land use per unit of beef production is higher.

In Table 1, the land area component is most negative (−5) for extensive pasture, degraded land (1A). Any farming method that results in land degradation is considered unacceptable by some consumers (scoring Z) (Özgüner, Eraslan & Yilmaz, 2012; Jendoubi *et al.*, 2020). The score for land area is high (−3) for most extensive grazing (1B) and −2 for beef production on fertilised irrigated pasture (2B), but −3 when concentrates are fed (2A). Feedlots and indoor housing require little additional land so the total land area equates to that needed during early development and the production of concentrates. Semi-intensive silvopastoral systems require the lowest total amount of land so their score is −1. Some of the land area for dairy-origin calves is allocated to dairy production, giving them a less negative score (−2) than that for beef-origin calves (−3).

(6) Efficiency of use of world resources: amount of water used

Water is often considered an inexpensive and widely available resource (Brew *et al.*, 2011; Palhares & Macedo, 2015). However, the water footprint of beef production and other activities (Mekonnen & Hoekstra, 2010) has become an increasingly important consideration, especially in areas with water shortages. Accounting for water that falls as rain and other precipitation, called 'green water' (Falkenmark, 1995) and distinguished from 'blue water' drawn from rivers and aquifers, can lead to double counting (Pfister *et al.*, 2017). Some green water drains into waterways and may have no impact on agricultural or other human activities, so green water may not be the best measure to use in a comparison of agricultural systems. In a comparison of four beef-production systems in terms of the amount of water used, only conserved water in farm reservoirs, human water supplies, or from rivers and streams was considered (Broom, 2019*b*). Some of this conserved water is already purified for human use. The conserved water used per kilogram of beef was: 673 l for feedlots where the pre-feedlot conditions were irrigated pasture, 553 l for feedlots where the pre-feedlot conditions were extensive pasture, 411 l for fertilised irrigated pasture, 155 l for extensive unmodified pasture, and 87 l for the semi-intensive silvopastoral system. The feedlot system used almost eight times as much water as the most water-efficient system (semi-intensive silvopastoral). Also, feedlot systems may use palatable water. This study used data from countries where water is sometimes in short supply, so the values may differ where water is plentiful. While water may be valued differently in different countries, climate change is increasing the frequency of droughts so the data used by Broom (2019*b*) may be increasingly representative in the face of a limited water supply.

The scores in Table 1 for the amount of water used, based on the calculations above, are most negative (−4) for feedlots, indoor housing and irrigated pastures because irrigated crop production for feed and irrigated pasture both have high levels of water consumption. Water use should be slightly higher for feedlots preceded by irrigated pasture rearing (3A and 4A) but this difference is unlikely to be large enough to warrant different scoring so all these production systems were scored −4. The lowest water use will be for semi-intensive silvopastoral systems (5), since they preserve water in the soil and vegetation, and this system was therefore scored zero. Dairy farming uses more water than beef farming so the score for dairy-origin calves is −4 while beef-origin calves are given the mean score of the commonest systems −3.

(7) Harmful environmental effects: greenhouse gas production

Some consumers now avoid animal products, especially beef, in order to reduce the extent of climate change. The main reason for this is information about the production of methane in animal agriculture, principally from ruminants. Initial publications emphasising this, e.g. that of the FAO (Steinfeld *et al.*, 2006), used calculations of carbon dioxide equivalents (CO_{2e}) that exaggerated the global warming effects of methane because they did not take into account the relatively short duration of methane in the atmosphere (Allen *et al.*, 2018). However, methane from cattle does have an important global warming effect. A second misleading aspect of the FAO calculations was that the data for CO_{2e} caused by cattle came from systems using extensive grazing and feedlots. Because there is much variation in CO_{2e} production amongst beef-production systems, these figures cannot be extrapolated to other systems and should be used with care in planning future food production. The analysis of de Vries & de Boer (2010) provided values for CO_{2e} of 3.9–10 kg for 1 kg of pork, 3.7–6.9 kg for 1 kg of chicken and 14 to 32 kg for 1 kg of beef. Their calculations include CO_2 from fossil fuel use, CH_4 and N_2O from manure, CH_4 from rumen fermentation, and also CO_{2e} from the cultivation and transport of feed. However, they found that greenhouse gas production can vary by a factor of 2–4 even among relatively efficient beef-production systems; some of that variation being attributable to diet (de Vries & de Boer, 2010). Dietary supplements and plants used in silvopastoral systems can reduce the population of methanogens in the gut of cattle, principally Archaea such as *Methanobrevibacter*, and hence reduce methane production per unit of beef. Anti-methanogenic compounds and plants that could be used in cattle husbandry but that may reduce productivity, include halogenated aliphatic hydrocarbons, nitroxy compounds, pterins, statins (some from fermented rice straw or garlic), fats, oils and fatty acids, tannins, flavonoids, saponins, ionophores such as monensin, and a range of plant species (Rira *et al.*, 2015; Patra *et al.*, 2017). There are thus possibilities for reducing methane production in beef cattle but this may be more difficult in the most extensive systems because feeding of anti-methanogenic supplements may not be feasible and palatable anti-methanogenic plants may not be available.

High-beef-yield systems, such as feedlots and semi-intensive silvopastoral systems where high-protein shrubs lead to high yield per unit area (Murgueitio *et al.*, 2008), produce less greenhouse gas per unit of beef than lower yield systems. This argument would also apply to other high-producing systems, such as some temperate pasture-only systems, especially those with protein-rich legumes incorporated into the pasture. For pasture-based Brazilian beef there were also large differences in total CO_{2e} with yield (de Figueiredo *et al.*, 2017; Balmford *et al.*, 2018). Considering total system emissions (enteric, manure, pasture and fertiliser), semi-intensive silvopastoral systems and the best-producing feedlot systems both produced about four times less CO_{2e} per tonne of beef than inefficient extensive pasture systems (Balmford *et al.*, 2018). Similarly (Murgueitio *et al.*, 2008; Broom *et al.*, 2013), methane production per unit of beef production was 1.6 times lower for semi-intensive silvopastoral systems than for fertilised pasture and 1.8 times lower than for an efficient unfertilised pasture system. The high production of beef per unit of land in the semi-intensive silvopastoral system could explain these differences. In all systems where food supplementation is used, the greenhouse gas cost will be higher. Organic systems produce more methane than systems not classified as organic but, because they do not involve synthetic fertilisers, their carbon dioxide and nitrous oxide (and hence global warming potential) output is overall lower (de Vries *et al.*, 2015). Organic systems had lower energy input than non-organic but, because their meat productivity per unit area was lower, they had higher acidification and eutrophication impacts (Alig *et al.*, 2012).

A comparison of beef systems between dairy-origin calves and suckler calves produced from beef cattle parents (de Vries *et al.*, 2015) found that the global warming potential of the latter was 41% lower in the dairy-origin calves. A similar result was obtained by Casey & Holden (2006). This is because the greenhouse gas cost over the life of the beef cattle mothers is all allocated to beef production, whilst for dairy mothers, it is allocated to milk production. Dual-purpose cattle had a lower global warming potential than dairy breeds with meat production as a minority economic output (Zehetmeier *et al.*, 2012).

Since tillage and other soil structure damage results in greenhouse gas production (Vellinga, van den Pol-van Dasselaar & Kuikman, 2004; Nawaz *et al.*, 2017), where arable crops contribute to beef cattle diet, greenhouse gas production per unit of beef will be higher. Not all life-cycle analysis studies take account of this. The conditions in which beef cattle are kept also have an effect on the soil, for example semi-intensive silvopastoral systems preserve a much greater depth of soil than grass-only systems which are more at risk of soil erosion (Molina *et al.*, 2008; see Section III.11 on carbon sequestration). Organic and other systems that preserve soil structure retain greenhouse gases whereas ploughing or other soil disturbance causes these gases to be released to the atmosphere.

Greenhouse gas production per unit of meat produced is highest for extensive, degraded pasture (1A) (scored −5). Since the attitudes of many scientists and some of the public are very negative towards climate change and greenhouse gases, especially if caused by avoidable actions as is the case with degraded pasture (Smith, Kim & Son, 2017), Z is.

scored in Table 1. Extensive pasture that is not degraded (1B) is scored −3, as are indoor-housed cattle with extensive pasture origin (4B). The high feed-conversion efficiency of feedlots, indoor housing and semi-intensive silvopastoral systems leads to a score of −1 although the system used during early rearing increases this score. Beef-origin calves are allocated the mean score of −2 while dairy-origin calves score − 1 because some of the greenhouse gas cost is attributed to dairy production.

(8) Harmful environmental effects: water pollution, N/P cycle disruption

Interference with world nitrogen (N) and phosphorus (P) cycles is another factor to be considered in comparisons (Rockström *et al.*, 2009). Artificial fertiliser is used in some feed-production systems and some pasture systems but not on unfertilised extensive pasture or semi-intensive silvopastoral systems. Nitrate pollution is more likely when artificial fertiliser is used. It is possible to manage conditions for keeping beef cattle so that water pollution by ammonia and other pollutants from manure is avoided, or at least minimised (Nader *et al.*, 1998). High concentrations of animals increase the risk of such pollution, but the localisation of animals in a small area can be associated with better opportunities to minimise N and P loss during storage and spreading of manure. In United States feedlots, 50% of nitrogen was lost (Eghball & Power, 1994). The lost N and P can enter waterways and the use of fertilisers on both crops and pasture increases the risk of water pollution (Gerber *et al.*, 2015) so systems with no fertiliser usage (extensive pasture, pasture with clover or other legumes and semi-intensive silvopastoral) produce less water pollution.

Water pollution is greater when there is a high density of animals and when concentrates are fed (Roche *et al.*, 2013). Hence extensive pasture (1A, 1B) and semi-intensive silvopastoral (5) are scored zero for this component. Fertilised pasture without concentrates (2B) is scored −1 and fertilised pasture with concentrates (2A) is scored −2. The high use of concentrates in feedlots and indoor housing results in 3A, 3B, 4A and 4B being scored −2, while the longer period of concentrate feeding in lifetime indoor animals (4C) is scored −3. Dairy-origin and beef-origin calves are both scored −2.

(9) Harmful environmental effects: on habitat conservation

While the effects on conservation are discussed separately here, Table 1 contains no entry for this component due to extensive similarity with the land area component. Forest or other natural habitat may be cleared to use land for beef production, with obvious conservation consequences. Beef production can take place on cleared land or on existing farmland with low agricultural productivity. Together with cases of high stocking density, these situations can lead to land degradation, again with conservation implications. Higher beef production per unit land area can be achieved in a number of ways, including managing the land to maintain the soil thickness and quality, planting more-productive forage plants, fertilising the land with manure or artificial fertiliser, irrigating, and avoiding over-grazing. The higher the meat production per hectare of land, the more land will be available for other purposes, such as conservation, which is becoming increasingly important to consumers (Balmford *et al.*, 2018). Systems that use high-protein shrubs and trees, and to a lesser extent high-protein pasture plants such as clover, increase productivity and hence reduce overall land use, potentially allowing land to be set aside for nature reserves.

(10) Harmful environmental effects: on biodiversity

Biodiversity can be evaluated in both pristine environments and in those modified greatly by humans, and both barren and diverse environments can be conserved, making biodiversity a different component from conservation. The degradation of land may result from clearing of natural vegetation, tillage of soil and planting of pasture or other agricultural plants, or the presence and actions of livestock. Over-grazing can lead to land degradation in any system. Degraded land, where soil and soil nutrients are lost and plant growth is reduced, has lower biodiversity than undamaged agricultural land but can regenerate to produce biodiverse environments (Plieninger & Gaertner, 2011). There is public concern about biodiversity loss and habitat degradation (Skogen, Helland & Kaltenborn, 2018). Most pasture has a lower biodiversity than the natural vegetation that was cleared to produce it (Koellner *et al.*, 2013), and the original, complex range of habitats is also lost. However, farmland with more trees and areas where natural vegetation is left at the margins of cultivated areas are more biodiverse than when every part is cultivated. Semi-natural pasture has higher biodiversity than pasture resulting from monoculture (Luoto *et al.*, 2003) and herbal leys can increase pasture productivity as well as biodiversity (Goh & Bruce, 2005).

In many countries, the biodiversity of farmland is now lower than it has ever been (Benton, Vickery & Wilson, 2003; Batáry *et al.*, 2020). The use of herbicides and pesticides on cultivated land can have a large impact on local, and hence global, biodiversity. When herbicides are widely used (particularly in monocultures), the food plants of insects, birds and mammals disappear (Butler, Vickery & Norris, 2007). The use of pesticides such as seed dressings and crop sprays results in lethal effects on non-target insects and other animals (Geiger *et al.*, 2010). These two agents have resulted in an enormous reduction in farmland biodiversity.

Pasture containing shrubs and trees as well as pasture plants has a much higher biodiversity than land with pasture only (Fischer *et al.*, 2010). The numbers of insects and birds on silvopastoral systems was much higher than on pasture areas in the same locality (Burgess, 1999; Fajardo, Johnston & Neira, 2008; Múnera *et al.*, 2008; Rivera *et al.*, 2008; McAdam & McEvoy, 2009). Extensive pasture systems have higher biodiversity than irrigated pasture and most crops such as maize and soya have less biodiversity than pasture (Cremene *et al.*, 2005; Zabel *et al.*, 2019). Areas where cattle are housed in a feedlot, or on slatted floors, are low in biodiversity and areas in which cattle feed, such as maize or soya, is grown are also quite poor. Early rearing on irrigated pasture will improve this biodiversity component of beef systems whilst early rearing on extensive pasture will show a further improvement.

In Table 1, biodiversity is scored −4 for degraded extensive systems (1A) and for systems requiring much concentrate feeding (2A, 3A, 4A, 4C). Extensive pasture that is not degraded (1B) is scored −2 while fertilised pasture with no concentrate feeding (2B) and feedlot or indoor housing preceded by extensive rearing (3B, 4B) are scored −3. Semi-intensive silvopastoral systems (5) are more biodiverse than extensive pasture but still less than natural habitats so are scored −1. When beef-origin calves are used, the biodiversity score is −2 as biodiversity is greater than for dairy-origin calves −3.

(11) Harmful environmental effects: on carbon sequestration

When land is converted from its original state to farmland or other human use, there is an effect on the amount of carbon sequestered in the soil and in the biomass above ground. Most farmed land was originally woodland or forest and many farming practices damage the soil in that they reduce its carbon-holding capacity, as mentioned above. The conditions in which beef cattle are kept have an effect on the soil, for example, semi-intensive silvopastoral systems preserve a much greater depth of soil than grass-only systems which are more at risk of soil erosion (Molina *et al.*, 2008). These systems also have a greater standing crop of plants, improving their carbon sequestration and hence, acting as a carbon sink (Schmidinger & Stehfest, 2012). While the carbon sequestration is greatest if shrubs and trees are present, permanent pasture is better in this respect than frequently renewed pasture, which in turn is better than land used for crop production (Garnett, 2009). Organic and other systems that preserve soil structure retain carbon better than when there is ploughing or other soil disturbance.

The reduction in carbon sequestration, in soil and above ground combined, below that in largely temperate native forest or woodland was found to be: 64% for arable land, 56% for pasture and 46% in agroforestry (Tzivilakis, Warner & Holland, 2019). In a tropical study the reductions were: 72% for arable land, 69% for pasture and 44% in agroforestry (Toru & Kibret, 2019). Figures for these actual reductions have been used to derive scores in Table 1, rather than data for the cost of compensating for reduction in carbon sequestration (Lubowski, Plantinga & Stavins, 2006). Degradation of pasture reduces carbon sequestration (Maia *et al.*, 2009) so the score is −4, while it is −2 for non-degraded extensive pasture systems. Where there is more crop usage, sequestration is scored more negatively. Fertilised pasture with feeding of concentrates derived from crops is scored higher than extensive pasture. All replanting of pasture with substantial soil disturbance reduces carbon sequestration. Dairy-origin calves may be a little more negative for carbon sequestration but the difference is too small to merit a different score from beef-origin calves, with both scoring −3.

(12) Genetic modification, 'fair trade', worker satisfaction and preservation of rural communities

The components referred to in this section are important sustainability topics but, at present, there is insufficient evidence for differences among systems to warrant a contribution to the total score, as explained below. Hence they are not included in Table 1, but negative effects may exist that could affect evaluation of the overall sustainability of beef or other animal products.

(*a*) *Genetic modification*

Many consumers will not buy products associated with genetic modification (GM), either because they do not agree with genetic modification of organisms or because of perceived risks associated with GM (Hudson, Caplanova & Novak, 2015). There is more antipathy to GM applied to animals or mixtures of animal and non-animal cells, than to plants or microorganisms (Knight, 2009). Genetic modification includes a variety of techniques such as gene editing, while cloning is not GM but does involve human interference in biological processes [see Chapter 11 in Broom (2014); Broom, 2018*a*]. Most people would not accept adverse effects of GM on human health, animal welfare, or the environment (Frewer *et al.*, 2014). For example, food from a genetically modified plant or animal potentially could contain allergenic proteins or could have unforeseen negative environmental impacts (EFSA GMO Panel, 2010). The welfare of animals may be poor because of the procedures involved or due to genetic changes in the modified individuals. Many people will not accept animal products if the feed of those animals was genetically modified: the potential that genetically modified plants (largely cereals and soya) are fed to cattle results in some consumers avoiding beef without a 'no GM feed' label, although this may be a small factor in sustainability assessment at present. For any product of genetic modification, including gene editing, legislation is in place in most countries requiring testing before general release. Such testing should involve a full range of aspects of sustainability (Broom, 2018*a*). Many beef producers, aware of consumer attitudes, thus express reluctance to use genetically modified or cloned animals due to the risk to beef sales. No GM animals are in current use in the beef industry, but beef production companies that use the most intensive systems may be more likely to use GM in the future.

(*b*) *Fair trade*

Failure properly to reward producers of food in developing countries is considered morally wrong by a proportion of consumers and, as a consequence, products like coffee, cocoa and fruit have a well-established 'Fair Trade' labelling system [Nicholls & Opal, 2005; see Chapter 8 in Broom & Johnson (2019)]. The substantial increase in interest in reliably labelled fair-trade products is an opportunity for beef producers but such labels are not yet widely used for beef products.

(*c*) *Worker satisfaction*

Working with animals such as cattle can be a rewarding occupation and employment in beef-production enterprises, most of which are in rural environments, is generally regarded as desirable (Viljoen & Wiskerke, 2012). Workers on semi-intensive silvopastoral farms in Colombia and Mexico, with high standards of animal welfare and environmental impact, report liking the work and stay in their jobs for longer than people who work on conventional farms (Calle, Montagnini & Zuluaga, 2009). In other beef-production environments, worker satisfaction requires investigation (Calvo-Lorenzo, 2018). Concerns within the beef-production industry about its future should be less when sustainable systems are used.

(*d*) *Rural community preservation*

Rural communities can decline and disappear as a result of agricultural and social system changes. Public pressure can then lead to government schemes to safeguard such communities. In the European Union, subsidies to preserve rural communities have reduced migration to cities, a major success of the EU Common Agricultural Policy (Gray, 2000; Broom, 2010). Some consumers prefer beef produced by small rural communities, which might confer some advantage for more extensive production systems.

IV. DISCUSSION

A scientifically based scoring system, including all components of sustainability, will be of value to policy makers, researchers, producers, organisations aiming to improve sustainability and the general public. Those carrying out sustainability scoring require a comprehensive knowledge of the scientific literature concerning each component. Those using the scoring information require that it be: based on scientific or other reliable information; comprehensive; and simple to understand, even if the analyses upon which it is based are complex. The scoring system presented herein, and exemplified by analysing an issue of key importance, could include positive as well as negative scores. The inclusion of an indicator of zero-tolerance (Z) for a sustainability component reflects quantitative information about public attitudes and helps to explain how sustainability is evaluated by the public. When there are several systems for production or action, the scoring method facilitates objective comparisons and emphasises that it may be misleading to refer to sustainability of a product as if it all was produced in the same way.

For every farming system, the most skilled farmers may be able to mitigate negative effects on components of sustainability better than the least skilled. Hence efforts are made here to portray the mean performance of systems, rather than the best or worst cases. The analysis summarised in Table 1 shows that some systems that are negative in one aspect of sustainability are less negative in others. For example, beef farming after early rearing on fertilised irrigated pasture (3A) was assessed as better than extensive grazing without pasture degradation (1B) in terms of greenhouse gas production and because it requires less land but feedlots are assessed as worse in terms animal welfare, land usage and amount of water used. The best beef-production systems are much better than the worst. The least sustainable systems, as indicated by the total scores in Table 1, are those involving indoor-housing on slatted floors with concentrate feed (−26 to −29) (Roath & Krueger, 1982; Broom & Kirkden, 2004; Duff & Galyean, 2007; Hall, 2008), extensive grazing where the pasture becomes degraded (−26) (Hall, 2008) and the two feedlot systems (−25) (Köhler, 1993). The zero-tolerance indicators for systems that are completely unacceptable to some consumers indicate that degraded pastures are unacceptable for two reasons. Other zero-tolerance scores are because some consumers find the poor welfare of indoor-housed cattle and cattle kept in feedlots to be unacceptable. Dairy- and beef-origin calves had scores of −22 and −20 respectively, and some consumers dislike the early separation of dairy calves from their mothers and the poor welfare of high-producing dairy cows. The systems that had the least negative sustainability scores were the semi-intensive silvopastoral system (−5), followed by extensive grazing on non-degraded pastures (−12) and fertilised irrigated pasture grazing with no concentrate feeding (−16). Table 1 did not include scores for cell-cultured meat, because insufficient information is available, but there are likely to be fewer negative scores than those for the least sustainable systems analysed.

What is the future for agriculture? Consumers increasingly express concerns about biodiversity and animal welfare (Tarazona, Ceballos & Broom, 2020). The cost of ensuring high welfare standards for beef cattle and sheep in extensive systems is less than for animals currently farmed at high density such as pigs, poultry and some farmed fish. It is likely that changes in consumer preferences will alter agricultural production rapidly throughout the world. Reduced consumption of animal-derived foods in affluent countries and reduced waste have the potential to contribute to reducing the environmental impact of food production and increasing food security.

Table 2. Possible actions to move towards sustainable farming

Suggested actions
Consider sustainability.
Reduce waste and environmental damage.
Manage soils better and minimise soil disruption, especially in areas vulnerable to soil degradation or loss.
Develop systems with a lower carbon footprint and greenhouse gas production.
Avoid inefficient use of plants.
Avoid inefficient nutrition of animals and poor welfare including poor health. Reducing stress reduces disease and improves productivity.
Use plant and animal species and strains adapted to local conditions.
Select genotypes for local conditions.
Use herbicides and pesticides for arable and forage production as little as possible and in a targeted manner. Avoid environmentally damaging products.
Use locally grown plants with high food value rather than transporting supplements or fertiliser.
Feed and select animals to change the gut microbiome and reduce greenhouse gas emissions.
Use precision agriculture to minimise water wastage and water pollution.
Manage manure to recycle and reuse nitrogen and other components.
In farm activities, minimise the use of energy to minimise carbon costs.
Use semi-intensive silvopastoral systems where possible.
Develop cell-cultured meat using plant nutrients.

Statements about the sustainability of beef production should take account of all aspects of sustainability and the wide range of systems for beef production. Not all beef production is from poor-quality land that becomes degraded rapidly, and not all beef is produced using soya and grains that humans could consume. High-concentrate diets for cattle may result in less greenhouse gas production but much of their food could have been used directly by humans (de Vries *et al.*, 2015) and some of the most productive systems carry associated ecosystem damage, such as the loss of habitat, soil erosion and sedimentation, nutrient run-off and leaching (Claassen, Carriazo & Ueda, 2010).

Potential actions to improve our use of world resources and move towards more sustainable farming are listed in Table 2, which summarises and extends points made by Gerber *et al.* (2015). Efficient world food production can occur in environments and using systems that: supply the needs of the animals, resulting in high standards of welfare for the animals produced; allow coexistence with a wide diversity of native animals, plants, microflora and microfauna; and are fair to the people who work in them. Although consumer forces are leading to changes in farm production, efforts towards sustainability should not only be determined by 'the market'. Many aspects will require control by governments and international agencies. If governments consider only short-term national interests, longer term problems involved in many aspects of sustainability will worsen. Laws are needed to control our interactions with non-human animals and to preserve our whole environment, not just the aspects of the environment that humans use. These laws should consider all animals and other living organisms (Broom & Johnson, 2019).

In much of the production of cattle and other ruminants, for many years farming interests have discussed grazing systems and the key plants therein. Trees and shrubs are often considered as competitors of pasture plants. Yet production from a mixture of herbs, shrubs and trees is much greater than from a pasture-only system. Some shrubs and trees provide good food for ruminants and other animals, including herbivorous fish. High-protein, nitrogen-fixing shrubs such as *Leucaena leucocephala* can be used as forage for ruminants in rotational grazing systems where a range of palatable plants are available to the livestock. Lists of some examples of the plants usable in such grazing systems in tropical, sub-tropical and temperate environments are provided in Broom (2017*b*).

Dramatic changes in agricultural systems are starting to occur. Some of these changes can be put into effect rapidly, but others will take much longer because they involve structural changes to farms, changes in markets and changes in the thinking of those in the agriculture industry. It appears that consumer demands are changing much faster than the industry and governments are responding. However, consumers can also be resistant to changes in the food they eat. In order for the right decisions to be made, measurement of all aspects of sustainability is essential. While this review begins such an assessment, further sophistication of measurement and monitoring of changing public understanding and attitudes is needed in future. Combining measures to produce a sustainability score would seem a useful step forwards, since some compensation among factors is valid, provided that factors for which there is zero-tolerance are also included. Our current world with accelerating environmental degradation and extinction of animal and plant species will need rapid changes to preserve key aspects of sustainability if we are to prevent extensive loss of life. Whilst some of the improvements in sustainability of agricultural systems could help to improve human welfare, human impacts are not the only issues as harms to non-human animals and to other living species are also matters of major importance (Tarazona *et al.*, 2020). There is already much public concern in all countries about the welfare of cattle and other farmed animals (Broom, 2019*a*). Some improvements in animal welfare can be made rapidly and with minimal costs to the consumer; others, such as system changes and those involving significant reductions in stocking densities, will take a longer time to implement and have a larger financial impact. However, the cost of such changes is low in comparison with the effects of a reduction in the market size if a substantial proportion of consumers stop buying the product.

V. CONCLUSIONS

(1) Sustainability is a wide-ranging concept with many components but statements about sustainability can be misleading when they neglect essential components.
(2) In order to evaluate sustainability, a simple scoring system is presented that produces a score that takes into account all relevant components. Scores are allocated using the available scientific literature concerning each component.
(3) The overall score allocated to each component also includes a category for factors that are unacceptable for some consumers.
(4) Using the example of beef production, the results show that there is a wide range in sustainability, with the best systems very much better than the worst systems.
(5) The sustainability components that could be assessed for beef-production systems included human health, animal welfare, land usage, land area, amount of water used, greenhouse gas production, water pollution and N/P cycle disruption, biodiversity loss and carbon sequestration.
(6) The least sustainable beef production systems were identified as extensive grazing that causes land degradation and the use of feedlots or indoor housing with grain feeding.
(7) Semi-intensive silvopastoral systems are the most sustainable beef-production systems and well-managed pasture-fed beef from land where crop production is uneconomic is also sustainable.
(8) The scoring system and results presented herein for beef production could be of value for policy makers, researchers, producers, organisations aiming to improve sustainability, and the general public.

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