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Sustainable, efficient livestock production with high biodiversity and good welfare for animals.

Running head: Silvopastoral systems: sustainability

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Abstract

What is the future for livestock agriculture in the world? Consumers have concerns about sustainability but many widely-used livestock production methods do not satisfy consumers' requirements for a sustainable system. However, production can be sustainable, occurring in environments that: supply the needs of the animals resulting in good welfare, allow coexistence with a wide diversity of organisms native to the area, minimise carbon footprint and provide a fair lifestyle for the people working there. Conservation need not just involve tiny islands of natural vegetation in a barren world of agriculture as there can be great increases in biodiversity in farmed areas. Herbivores, especially ruminants that consume materials inedible by humans, are important for human food in the future. However, their diet should not be just ground-level plants. Silvopastoral systems, pastures with shrubs and trees as well as herbage, are described which are normally more productive than pasture alone. When compared with widely-used livestock production systems, silvopastoral systems can provide efficient feed conversion, higher biodiversity, enhanced connectivity between habitat patches and better animal welfare so they can replace existing systems in many parts of the world and should be further developed.

Keywords: sustainability; silvopastoral; livestock; biodiversity; animal welfare; conservation;

Some world ecosystem questions

Some landscape is perceived by biologists and the public to have value that is real as opposed to financial and is recognised by international conventions, e.g. the European Landscape Convention [1]. One valued landscape is upland grazed land, for example in the Pyrenees and other part of Europe [2]. Such areas are much influenced by farming and very different from the original upland habitat but many would attest to their value. Are they as important as upland woodland? Aspects of the value of land include ecosystem services [3-8] such as water flow regulation, provision of harvested goods, biodiversity preservation and climate stabilisation via carbon storage in vegetation and soils. Swetnam et al [8] refer to the value of intact ecosystems, meaning those that are not modified by human activity, but the distinction between modified and unmodified is not always possible or useful. Many of the arguments and quantitative methods developed to calculate value would apply to ecosystems that are partially modified from their original state. Ecosystems subject to some human exploitation can have much biodiversity [9]. The component parts of ecosystems also have value. Populations of charismatic species are of particular interest to the general public and the lives of the human and non-human individuals present are also valued. Indeed for many people, the welfare of animals in an area of land is valued more than any other part of the overall system.

Biodiversity is declining in the world, mainly because of farming [10]. Of the total land surface of the world, 33% is used for livestock production [11]. The proportion may well increase in the future so how should livestock areas be managed? Livestock production in Latin America and the Caribbean area has been increasing and today corresponds to 27.1% of the land [12]. Of the 22 million hectares of forest lost between 1960 and 1995, 21 million hectares were then used for cattle production. In tropical regions of the world, annual deforestation rates increased between 2005 and 2010 by 8.5% from an average loss of 10.4 million hectares per year in 2005 [13,14]. Widespread livestock production methods are increasingly viewed as unsustainable, even as the antithesis of conservation [15] and are questioned in relation to animal welfare [16]. One solution, if current widespread animal production systems are used, is to reduce livestock production. Another solution is to use sustainable livestock production methods with much greater on-farm biodiversity than in normal production, no increase in land use and better welfare for the animals [17,18,19].

The concept of biodiversity includes the extent of variation when the differences considered are genetic [20], biologically functional [21], or based on ecosystem type [22]. Biodiversity may be described numerically [23,24] or by other means [25]. How can adverse effects of livestock production on biodiversity be minimised? Green et al [26] explained that the increase in world food demand, including especially increased demand for animal products, will lead to a reduction in the extent of habitat for wild species of animals and plants and that two solutions for how to reduce this impact have been proposed. One of these is wildlife-friendly farming while another is land sparing and consequent availability of land for nature reserves [27,28]. Green et al produce a model that shows how, to date, farming for species persistence has often depended on demand for agricultural products and how population densities could change with agricultural yield. Land sparing alone leads to islands of ecologically valuable areas in a 'desert' of farmland. A combination of land sparing and sustainable farming [29,30] can promote good welfare in animals and much greater in situ biodiversity than occurs in the widely used agricultural systems.

Sustainability

Profitable operation of a system and demand for its products are not sufficient reasons for considering it to be sustainable and continuing production [31]. Systems were initially called unsustainable when a resource became depleted so much that it became unavailable to the system, or when a product of the system accumulated to a degree that prevented the functioning of the system. Now the meaning of the term is much wider, for example a system can be unsustainable because of negative impacts on human health, animal welfare, or the environment (see Table 1). Hence a different definition is needed. *A system or procedure is sustainable if it is acceptable now and if its effects will be acceptable in future, in particular in relation to resource availability, consequences of functioning and morality of action* [32,33]. With more criteria for unacceptable harms [34], sustainability is harder to achieve and unsustainability may be reached long before, the production system itself fails. What the public accepts can also change, for example some degree of resource depletion may be tolerated.

Members of the public in all parts of the world, particularly in developed countries, are now insisting on transparency in commercial and governmental activities and on changes in methods of producing of various products. There is a gradual changeover from a “push society”, driven in the case of animal production by the producers of the animals, to a “pull society”, driven by consumers and facilitated by governments and food retail companies [33,34]. Increasing numbers of consumers now demand ethical production systems and refuse to buy products where production involves, for example, inhumane slaughter methods, rearing calves in small crates, unnecessarily killing dolphins in tuna nets, or the payment of very low prices to poor farmers in developing countries. As a consequence, many systems developed with consideration of only short-term market factors, even if widely used at present, are not sustainable. This means that, in some countries, the public have already demanded that such systems do not continue. Throughout the world, the public are likely to make such demands in the relatively near future. The first steps may be the setting up of supply for niche markets but the rapidity of increase in consumer pressure is likely to lead to change away from the most unacceptable systems [35] Changes with small economic cost are likely to occur faster than changes with more substantial cost. One of the first examples of consumers forcing change is the gradual disappearance of animal production procedures with poor welfare for the animals [31-34]. It may be that, in future, consumers will not tolerate very low biodiversity in farmed areas.

Sustainable silvopastoral production of cattle and other animals

Cattle production for meat, milk, or other products may waste valuable resources in that much of the animal feed could be consumed by people or the land used to grow human food instead. Additionally, the animals may be kept in such a way that their welfare is poor and, in relation to growth of feed and keeping of animals, there may be adverse impact on the local and world environment. Current cattle production is mainly in large cleared areas in which only herbaceous plants are grown as forage, together with buildings for housing the animals or materials related to production. The effects on the local environment include, initially the removal of trees and shrubs and secondly planting to produce a plant population comprising one, or a very small number, of species. In order to maintain monocultures of pasture plants, herbicides are widely used and biodiversity declines greatly. In addition there is use of land because of construction of roads and buildings, contamination of soil and waterways by agricultural chemicals, carbon cost resulting from CO_2 production from vehicles and from the manufacture of materials used, contamination of water by animal excretions [36] and methane emissions from the animals and their products. In systems at low or moderate altitude in tropical countries, plant growth rate is relatively fast and there are often disease and parasite problems. However, modification of cattle production systems to utilise land resources more effectively, to improve animal welfare and to increase biodiversity concomitant with providing a satisfying and profitable production system [17], is possible in temperate and tropical environments.

A cattle production system is explained here whose characteristics and aims include: using three-level or other multi-level production of edible plants, managing the soil taking account of worms and water retention [11], encouraging predators of harmful animals, minimising greenhouse gas emissions [37] improving job-satisfaction for stock-people, reducing injury and stress in animals and maximising good welfare, considering how to encourage biodiversity using native shrubs and trees, and utilising the potential for obtaining wood from trees.

If plant-consuming farm animals, especially ruminants, are fed leaf material, rather than grain, plant resources otherwise unavailable to humans are utilised. Although ruminants are of key importance for the sourcing of food for humans in the future, excessive focus on pasture plants for the feeding of farmed ruminants has been a major mistake in almost all parts of the world [38}. Shrubs and trees with edible leaves and shoots, in combination with pasture plants, produce more forage per unit area of land than pasture plants alone. For millennia, trees have often been left in pasture areas, or planted there. Both trees and shrubs can provide shade from hot sun, and shelter from precipitation as well as fulfilling the need of animals to hide from perceived danger [16]. They can also be a substantial source of nutrients for ruminants and other animals [39-43].

Agro-forestry has been characterised [44] as being: intentional combination of trees with crops or livestock, intensive in that active management is involved, integrated to enhance the overall productivity of the area and interactive in that the biophysical interactions of component species are manipulated and utilised. Both selection of plants and management can maximise positive, facilitative interactions among species and minimise negative, competitive interactions [45]. Competition for light can result in a negative impact of trees on pasture plant productivity, in particular if the plants have a C4 photosynthetic pathway with light saturation points at about 85% of full sun. However, pasture plants with a C3 photosynthetic pathway and light saturation photosynthesis at 50% of full sun will not have their growth or yield adversely affected by certain degrees of tree shade [46]. Indeed shade may improve growth in some pasture plants. Shading increased the protein content, and hence the nutritive value to stock, of the grass *Panicum maximum* in laboratory conditions from 9.6% in Tanzania cultivar plants placed in full sunlight to 12.9% with 54% shading and, in Masai cultivar, 10.5% in sunlight to 15.9% in shading [47]. Nutrient accumulation under woody plants can have long-term beneficial effects for pasture plants [48]. There are complex interactions between foraging ruminants and both plant growth [49] and plant survival [48].

Many of the trees used in agro-forestry have leaves and shoots that are toxic or inedible but in some cases, the tree species used can provide nutrients for farmed animals, for example the fruits of shade trees and some “live fences” [50]. However, it is the planting as forage plants of both shrubs and trees whose leaves and small branches can be consumed by farmed animals that is transforming the prospects for sustainable animal production systems. “Fodder trees” have been used in several countries e.g. tagasaste *Chamaecytisus palmensis* is widely used by commercial farmers, mainly for cattle feed, in Australia. Individual farmers have pioneered silvopastoral systems, for example in Valle de Cauca, Colombia since 1990. Their feasibility, profitability and consequences for biodiversity have been investigated in detail [51-53].

The key aspect of silvopastoral systems is that the planted food for the animals is not just at the herbaceous level (Figure 1). A shrub layer composed of plants that can be eaten by the cattle or other stock is planted and also, in some cases, trees are grown whose leaves can be eaten, whilst fallen fruits can also be consumed. The leaves on the lower branches of trees may be browsed directly or branches can be cut for feeding to stock [54]. Shrubs that are especially suitable for planting as extra food for cattle include *Leucaena leucocephala* and other species of *Leucaena.* This leguminous shrub, native to Yucatán in Mexico, has long been used by the Mayans. Recently, it has been used in Northern Australia, Africa, Cuba, other parts of Mexico [55-57]. and South America. *Leucaena* is very palatable to cattle, fixates nitrogen, grows very rapidly in tropical conditions and is tolerant of drought [58]. In Colombia, *Leucaena leucocephala* has been planted in intensive silvopastoral systems at a density of 10,000 to 30,000 shrubs per ha with pasture plants: *Cynodon plectostachyus, Cyperus rotundus, Dicanthium aristatum, Panicum maximum* and *Botriochloa pertusa* [59,60]. Other studies of the combination of trees and pasture plants have been carried out in Veracruz and Jalapa, Mexico [19,61]. A range of tree species, whose leaves and shoots can be eaten by livestock, can be grown in different climatic areas. In the tropics and sub-tropics of South and Central America, trees that have been used include the leguminous tree *Gliracidium sepium* that has high protein, phosphorus, potassium and magnesium in its leaves [62]. Other species with high protein utilisable by ruminants are *Moringa oleifolia,* in drier areas, *Trichantera gigantea* and *Morus alba* {63[.

Since *Leucaena leucocephala* is very palatable to cattle, the animals have to be put in each newly planted area for a short time only, so that they do not damage the plants to the point where they cannot rapidly re-grow. In order to solve this, in silvopastoral systems in Colombia and Mexico a rotational strip system, often separated by electric fences, is used with each group of cattle being moved on every day or every few days. The cattle typically eat the new growth of the *Leucaena* before eating the new grass [60].

If silvopastoral systems are to be advocated, it is important to consider in what circumstances leaf production that is available for domestic animal consumption can be greater than in pasture-only systems. Table 2 shows, as an example, fodder production in Colombia of a mixed planting of *Leucaena leucocephal*a with the grass *Cynodon plectostachyus* in comparison with a monoculture of the pasture plant. Of the material available to cattle, the dry matter production was 27% better, the crude protein production 64% better and the metabolisable energy 23% better in the silvopastoral system [58].

If ruminants are consuming the plants, their growth and milk production are appropriate measures of the quality of the forage. Milk production in a tropical silvopastoral system, similar to that referred to in the previous paragraph, was 4.13 kg per cow per day as compared with 3.5 kg per day on pasture-only systems. As the numbers of animals per ha was much greater, production of good quality milk per ha was 4-5 times greater on the silvopastoral system [64]. Milk production from cattle kept on degraded conventional pastures in the humid tropics is very low and, whilst it can be increased by adding appropriate fertiliser, it can also be greatly improved by silvopastoral system use. Milk production from a silvopastoral system in Colombia, with 4.3 dairy cows per ha. and no artificial fertiliser, was 16000 l. per annum per ha. The mortality rate was low and the calving interval 12.8 months [18,59]. Milk production can be significantly increased when cattle are able to eat tree leaves in substantial quantities as well as pasture [65]. Milk production on a good quality pasture of the grass *Pennisetum clandestinum* was 12.8 litres per cow per day [66]. However, if the cows were also able to eat the leaves of the tree *Alnus acuminata,* the milk production was 14.4 litres per cow per day. In financial terms, the increase in income per cow was from 3152 to 3552 U.S. dollars per cow [64]. If supplements fed to cattle were 75% *Tithonia diversifolia,* a fodder shrub in the family Asteraceae, instead of just conventional concentrates, the milk productivity was increased [60].

Soil, nutrients and fertiliser use: silvopastoral and other systems

Much of the structure of the soil is retained in silvopastoral systems with the consequence that earthworms and other soil invertebrates flourish to a greater extent than on land that includes only pasture plants [59]. The presence of deep tree roots, or relatively deep shrub roots, and the maintenance of complex soil structure, has the consequence that water is retained better by the soil in these systems [48]. A further consequence is a reduction in nutrient leaching to ground water. The deep roots of trees and shrubs are capable of retrieving nitrates and other nutrients that have leached below the rooting zone of herbaceous plants and of eventually recycling these nutrients as litterfall and root turnover in the cropping zone. This role of tree roots has been observed in many cropping systems studied [67]. A silvopastoral system in

Florida on flatwood soils (spodosols) was more likely to retain nutrients within plants as compared with plants in an adjacent fertilised pasture with cattle grazing [68]. A comparison in Colombia of soils from conventional pasture for over 30 years and a silvopastoral system for 3, 8, or 12 years found that while % carbon and % organic matter depended on amount of clay in the soil, microbial biomass, estimated by total ester-linked fatty acid methylated esters, and activities of enzymes such as β-glucosidase, alkaline phosphatase and urease were higher in older silvopastoral areas than in conventional pasture [69]. Conventional pasture favoured gram negative bacteria while silvopastoral systems favoured actinomycetes and fungal biomass and there were islands of extra soil fertility under the canopy of trees [70]. Plant growth is thus favoured, as are the production of milk and other animal products.

Silvopastoral systems can result in better conditions for beneficial insects with consequences for soil composition and diversity of plants in the system. Fertilised *Cynodon plectostachyus* pasture and a silvopastoral system with two grasses, *C. plectostachyus and Panicum maximum,* and the shrub *Leucaena leucocephala*, were compared using areas of each system on the same farms in Colombia and the numbers of dung beetles were higher in the silvopastoral system [68]. There were 5 species in silvopastoral: three in fertilised, 1.4 times more dung removed per beetle on silvopastoral, 2.7 times as much dung calculated to be removed in total, and 1.8 times as many seeds deposited by the beetles. Horn flies *Hydrotaea irritans* cause irritation to stock and can transmit disease [71]. The numbers trapped on a silvopastoral system were 40% lower than on pasture, probably because of more rapid dung removal and increased numbers of predators of small insects.

The presence of readily degraded manure from the livestock on the pasture and of nitrogen fixing plants in the silvopastoral system, is associated with retention of calcium and phosphorus [58]. One of the advantages of using a nitrogen-fixing shrub species such as *Leucaena leucocephala*, is that artificial nitrogenous fertilisers are not needed, just supplementary metals in some circumstances [72]. This is a major factor in sustainability as the carbon cost of producing, transporting and applying artificial nitrogen fertilisers is very high.

Impact of silvopastoral systems on biodiversity and welfare

A dramatic consequence of the use of silvopastoral systems is the increase in biodiversity as compared with pasture-only systems [73,74]. The presence of shrubs and trees very greatly increases cover for wild birds, mammals and reptiles. The greater range of plants increases the number of larger insects and the more complex soil increases soil insects and other invertebrates. The number of species of birds reported [75] from four areas of silvopastoral systems in Colombia were 108, 135, 137 and 214. The silvopastoral cultivated areas had three times as many bird species as pasture areas without trees in the same region. In another area there were 24 bird species on pasture without trees, 51 species in woodland and 75 species in silvopastoral systems [76]. Some species in woodland were not present in silvopastoral systems but the impact on biodiversity is clear. There were 30% more ant species on a grass and *Leucaena* system in Colombia, than on grass only, although the major factor affecting ant species numbers was the presence of large trees [77]. Despite these species numbers, there are many plants and animals that are not able to live in silvopastoral farmed land as they require dense forest, extensive marshland or other unmodified habitat in order to survive [78]. For their preservation, separate reserve areas are needed.

With increased biodiversity in silvopastoral systems, some of the birds and larger insects whose numbers are increased are predators on ticks so the numbers of ticks per ha. are reduced and the prevalence of tick-borne disease reduced. After the implementation of silvopastoral systems and a strategy for the integrated management of ticks, the incidence of anaplasmosis fell from 25% to below 5% in Valle del Cauca, Colombia [79]. In the Cesar region of Colombia, where routine chemical tick control had been needed every three weeks, the farms that replaced treeless cattle ranching with silvopastoral systems kept tick numbers low without any chemical tick control [79]. Since tick-borne disease is a major cause of impaired production in tropical animal production, the impact of the tick predators is of considerable economic importance.

Reduction of ticks, and hence of disease, improves cattle welfare as does reduction of starvation, over-heating and injury [16,80]. In addition to disease reduction, other aspects of poor welfare are also reduced by the presence of shrubs and trees. Starvation is less likely in the silvopastoral systems, which provide a diet with good nutritional composition in dry seasons, than in pasture-only systems. High temperatures can also cause poor welfare but the shade provided by the shrubs and trees reduces the risk of over-heating. Cattle skin temperatures in a silvopastoral system were 4C lower than in a pasture-only system [81]. In addition, in some of the systems, the animals have reduced anxiety and fear associated with increased possibility for partial or complete concealment [82]. Even without full concealment, animals in the silvopastoral systems appear more calm and less disturbed by human approach. Such behaviour can be quantitatively evaluated and indicate good welfare. Mancera and Galindo [19], using a range of welfare indicators [83], have shown that the fear response of cattle in areas with more trees is lower than in cows kept in grazing paddocks with fewer trees. They found a reduction in the number of cattle in poor body condition in areas with trees than in areas without trees but with equivalent pasture provision and fewer agonistic interactions than cows with no shade, possibly as a result of the increased stability of the social groups. In a comparison of monoculture and silvopastoral paddocks in Yucatán, Mexico, cattle in the silvopastoral paddocks showed some indication of more cohesive social behaviour and 44% longer resting times. The foraging times were reduced by high temperature and humidity in the monoculture paddocks but not in the silvopastoral paddocks [84].

Working conditions for stock-people in silvopastoral systems

Sustainability, as defined here, has a human worker component [85]. Workers on silvopastoral farms in Colombia and Mexico, where animal welfare and environmental impact are good, report they like the work and stay in the job longer than people who work on conventional farms [86]. Farmers who adopted silvopastoral systems in the Quindío region of Colombia mentioned different work values as benefits of their new cattle ranching: an increased environmental awareness among workers (29% of employers mentioned it), more initiative and curiosity from employees (21%), a perspective of future job improvement from new knowledge on silvopastoral systems (11%) and reduced social conflict from illegal logging and intrusion (7%) [86]. Several countries have incentive programmes for rural communities, based on payments for ecosystem services.

Greenhouse gas production and nitrogen usage in silvopastoral systems

The use of shrubs and trees, as well as pasture plants, in animal production systems reduces greenhouse gas production in several ways [58] (Table 3). Firstly, carbon loss from growing plants in silvopastoral systems is lower. Secondly, the loss of carbon from soil is less because the structure of the soil is maintained better. Thirdly, where trees are browsed, the area is more likely to be used continuously rather than for a short period so there is less carbon loss when the trees or other plants are removed. Fourthly, there is reduced methane production from ruminant animals feeding in the system. Intensive silvopastoral systems produced 12 times more meat than extensive systems, and 4.5 times more meat than "improved" pastures [87]. Methane emissions increased in a lower proportion: 6.8 and 2.8 times respectively. Thus, methane emissions per tonne of meat in intensive silvopastoral systems are 1.8 times lower than in extensive cattle ranching. Since three-level production is very efficient in providing food for livestock, less land is needed for a given amount of animal production. More production per unit area of land can result in less greenhouse gas emission in the world [18,88].

In a silvopastoral system using hybrid poplar (*Populus* spp.) at a density of 111 trees ha^{-1}, the net annual carbon sequestration potential could be as high as 2.7 t ha^{-1} yr^{-1}, whereas in a monoculture pasture system, the net annual carbon sequestration potential might be less than 1.0 t ha^{-1} yr^{-1} [89]. Silvopastoral systems with fast growing tree species therefore have the potential to sequester between two and three times more carbon than monoculture pasture systems. A net annual carbon sequestration rate of 2.7 t ha^{-1} yr^{-1} is equivalent to an immobilisation rate of 9.9 t of atmospheric CO_2 ha^{-1} yr^{-1}. The total carbon sequestered in the permanent woody components of the fast-growing hybrid poplar, together with the carbon contribution to soil from leaf litter and fine root turnover, was approximately 39 t C ha^{-1}. Theoretically, this implies that this system has immobilised 143 t of CO_2 ha^{-1} but 67.5% of the C, added via leaf litter and fine roots, was released back into the atmosphere through microbial decomposition so the net annual sequestration potential from the trees alone is 1.7 t C ha^{-1} yr^{-1} or approximately 6 t of CO_2 ha^{-1} yr^{-1} [88]. It has been estimated [90] that carbon-neutrality for the entire Chilean Patagonian cattle industry could be achieved by adopting silvopastoral systems on less than 1% of the total area of the region. However, this calculation might be correct only during tree growth.

Much supplementary nitrogen is typically used in agriculture but most sources are declining and the usage of energy in fertiliser production and in transport of fertiliser to farms is a sustainability factor. *Leucaena leucocephala* and several other shrubs and trees, such as red alder *Alnus rubrus* [90], used in silvopastoral systems fix nitrogen to the extent that supplementary nitrogen is usually not needed. Future farming systems are more likely to be sustainable if they incorporate nitrogen-fixing plants. For systems involving animal production, there has often been use of rotations with nitrogen-fixing plants grown for only part of the time. There will normally be less nitrogen fixation in such systems than in those in which the nitrogen fixers are present for longer periods, perhaps almost continuously. Indeed, *Leucaena leucocephala* and the mulberry *Morus alba* are sometimes called "protein banks". The use of nitrogen-fixing plants native to the area will have the consequence that biodiversity is further increased.

Temperate and other silvopastoral systems

Forest grazing or browsing in areas managed by humans has long been used in many parts of the world [54]. In oak and pasture systems in the Spanish and French Pyrenees, where many of the trees are *Quercus pyrenaica*, oak leaves may form 25% of the summer diet of goats and 2.5% of that of sheep, while both species eat acorns when these become available [92]. Some silvopastoral systems in Portugal, the Mediterranean region and parts of Western Asia use planted chestnut trees *Castanea sativa* or *C. mollissimum.* In many chestnut coppice systems, the major nutrient intake by goats and pigs is understorey plants from April to July, tree leaves from July to October and the fruits of the chestnut from October to December. Chestnut leaves have 12-14% crude protein [92]. Olive (*Olea europea*) leaves have 12% crude protein and 43% digestible organic matter. Other species of tree used are: *Quercus suber*, *Q. ilex, Alnus nepalensis*, *Sesbania sesbana* and *Pinus radiata*.

The roles of separate conservation areas and of universal biodiversity increase

Some wildlife can only survive if unmodified forest, marshland, heathland, or other natural habitats are available. These habitats have to be of sufficient area for the range utilised or required by the species. Hence nature reserves with little or no human modification are needed in many parts of the world. However, much of the world, probably an increasing amount [27], will be used for animal production and these areas can be very greatly enriched, in terms of biodiversity, if shrubs and trees as well as pasture plants are present. If they form wildlife corridors, for example along water-courses, their impact on world biodiversity is likely to be increased [68]. Although people are unlikely to pay to see pasture without trees, the greatly increased numbers of birds and other wildlife in silvopastoral systems with trees may offer economic opportunity for ecotourism. A combination of nature reserves and large areas of species-rich systems, in which the welfare of the animals produced is good, is likely to be demanded by an increasing proportion of the public in all parts of the world.

System uptake by farmers

Are silvopastoral systems likely to be taken up by farmers? Agroforestry methods and new forage plants have often not been readily used by farmers. Some systems have not spread because a financial return takes 3-6 years [93]. Lack of security of land tenure may also deter farmers from investing in future yields. However, the planting of *Leucaena* as part of a silvopastoral system can lead to substantial forage availability within nine months in tropical conditions. A further cost of some innovative changes in forage plants is that of maintaining the plant system. The nitrogen-fixing plant has to grow well in competition with pasture plants and *Leucaena* certainly does so. Palatable shrubs have to be protected from destruction by grazing or browsing animals, for example by limiting time in the forage area. There is some cost associated with moving animals and electric fences but extra plant production compensates for this. There seems to be increasing usage of silvopastoral systems in several tropical and temperate countries.

Conclusions

Animal protein from herbivorous mammals is important for providing human food. When ruminants are farmed, and they are fed materials that cannot be digested by humans, such as leaves and other cellulose-containing tissue, there is a positive net effect on human food provision. However, can ruminant production systems be sustainable? A system or procedure is sustainable if it is acceptable now and if its effects will be acceptable in future, in particular in relation to resource availability, consequences of functioning and morality of action. The advantages of silvopastoral systems for increasing biodiversity, improving animal welfare, providing good working conditions and allowing a profitable farming business are such that these systems are sustainable where many other large herbivore production systems are not. With good management, silvopastoral systems can replace existing systems in many parts of the world, reducing agricultural expansion into conservation areas. There should be further work developing them.

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Table 1 - Reasons for lack of sustainability of a system Modified after [34]

1. resource depletion	-	to level that is unacceptable.
	-	to level that prevents system function.
2. product accumulation	-	to level that people detect and find unacceptable.
	-	to level that affects other systems in an unacceptable way.
	-	to level that affects the system itself, perhaps blocking its function.
3. other effect	-	to level that is unacceptable.

The consequences of acts or of system functioning (in 1, 2 and 3) could be unacceptable because of immediate or later:

[a] harm to the perpetrator	:	resource loss or poor welfare
[b] harm to other humans	:	resource loss
[c] harm to other humans	:	poor welfare
[d] harm to other animals	:	poor welfare
[e] harm to environment including that of other animals.		

Table 2 Changes in nitrogen use and plant production, in an area where cattle were consuming the plants, after a monoculture of a pasture plant *Cynodon plectostachyus*

was replaced by the pasture plant plus the leguminous shrub *Leucaena leucocephala.* Modified after [58]

Variable (per year)	**Monoculture of** ***Cynodon plectostachyus***	**Silvopastoral system of** ***Leucaena leucocephala*** **(10,000 ha $^{-1}$) with** ***Cynodon plectostachyus***	**Difference %**
Nitrogen fertiliser ha $^{-1}$	184	0	-100
Biomass tonne ha^{-1}	23.2	29.9	+29
Crude protein tonne ha $^{-1}$	2.5	4.1	+64
Metabolisable energy Mcal ha $^{-1}$	56.9	70.2	+23
Calcium Kg ha $^{-1}$	83.2	142.3	+71
Phosphorus Kg ha $^{-1}$	74.0	88.8	+20

Table 3. Meat production and carbon emissions in three cattle production systems in Colombia [58] and CIPAV data

MEASURE	**Conventional extensive pastures**	**"Improved pastures" without trees**	**Intensive silvopastoral system**
Animal load (large animals ha^{-1})	0.5	1	3
Per animal weight gain (kg day^{-1})	0.37	0.5	0.75
Per hectare weight gain (kg ha^{-1})	0.185	0.5	2.25
Average methane emissions (kg ha^{-1} yr^{-1})	15.5	38	105
Annual meat production – live weight (kg ha^{-1} yr^{-1})	67.5	182.5	821.3
Methane emissions per tonne of meat (kg ton^{-1})	229.5	208.2	127.9
Land area required to produce 1 tonne of meat per year (ha)	14.8	5.5	1.2

Figure 1. Cattle browsing *Leucaena* in a silvopastoral system, Caribe, Colombia. (Photograph Walter Galindo, CIPAV) 460x345 mm., 180x180 DPI)

Media summary

What is the future for livestock agriculture in the world? Many widely-used livestock production methods do not satisfy consumers' requirements for a sustainable system.

However, herbivorous animals eat materials that humans cannot eat and production can be sustainable. Silvopastoral systems include shrubs and trees with edible leaves or fruits as well as herbage. They normally produce more animal food than pasture alone, have much higher biodiversity, provide for the needs of the animals resulting in good welfare, minimise carbon footprint and provide a fair lifestyle for farm workers. Hence they can replace existing systems in many parts of the world.