Assessing multifunctionality in relation to resource use – A holistic approach to measure efficiency, developed by participatory research

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Abstract: *Today's intensive agriculture needs to be transformed into sustainable production of food, and this process requires good tools that can assess whether an action is leading towards this in the long term. A critical issue is what optimal yield comprises in terms of other functions of agriculture, as higher yields might lead to e.g. a reduction in biodiversity or soil carbon. In this study, emergy analysis and footprinting were combined to assess and illustrate the total resource use caused by a farming activity (milk production) and to identify the renewable fraction of this resource use. The total efficiency was defined as a function of the resource use and the multifunctionality of production. The classification of ecosystem services in the Millennium Ecosystem Assessment (MA) was used as the basis for ranking multifunctionality. The results were expressed in the form of ecosystem bundles for the four MA categories (provisioning, supporting, regulating and cultural functions). Three scenarios with different degrees of input intensity and milk production were constructed and compared with the current production mode. The ratio of local renewable resource use to total resource use differed greatly between the different production strategies, being 1:3 for a self-sufficient organic farm and 1:14 for a conventional farm with maximum milk yield. Milk production was five-fold higher on the conventional farm, while generation of ecosystem services increased with increasing self-sufficiency under the local conditions prevailing in the study. Ecosystem services in all categories except provisioning were ranked higher when self-sufficiency increased.*

Keywords: *Emergy analysis, footprint, ecosystem services, ecosystem bundles*

Introduction

The global environmental crisis clearly shows the need for assessment methods that are able to relate to the complexity of the natural world and help us transform the current food system into a sustainable system (Rockström et al., 2009). We need to develop a system than can sustain production of sufficient food, allowing fair distribution and maintaining production capacity in the long run. This requires a production system that does not compromise the health and integrity of local and global ecosystems.

Global food demand is projected to increase by up to 70% in the coming 50 years (FAO, 2009). This challenge will be enormous, taking into account that large areas formerly known as the world's granaries are likely to be compromised by the global environmental crisis (Brown, 2009; IPCC, 2007).

Furthermore, the United Nation initiated Millennium Ecosystem Assessment (MA) found that about 60% of the assessed ecosystem services were being used faster than their rate of regeneration. Fundamental services for human well-being, and not least for food production, are in danger (Millennium Ecosystem Assessment, 2005). This concerns services such as the availability of fresh water, the productive capacity of seas, the maintenance of genetic resources and the ability to mitigate natural hazards. Human activities have now exceeded at least three of the nine boundaries within which we need to remain in order to function safely on Earth. With our present impact on the global climate and on global nitrogen cycling, as well as our contribution to the rapid reduction in biodiversity, we can expect unpredictable and uncontrollable changes (Rockström et al., 2009). Added to this is the issue of peak production of energy from fossil fuels (Bentley, 2002). This will have dramatic effects on the industrial mode of food production predominant in many countries today.

Abundant access to cheap energy have been fundamental for an agricultural system that unreservedly relies on fossil fuel-based inputs.

The development of farming systems that have high water, nutrient and energy use efficiencies and conserve natural resources and biodiversity without compromising yield is of the utmost importance. International research and consultation bodies such as FAO (Food and Agriculture Organization of the United Nations) and IAASTD (International Assessment of Agricultural Science and Technology for Development) have concluded that larger opportunities lie in small-scale farming than previously thought (Beintema et al., 2008; FAO, 2007; Ong´wen and Wright, 2007). One important reason identified was the high productivity and the generation of environmental services in such agriculture.

When assessing the multifunctionality of an agricultural activity, multi-criteria tools to evaluate productivity and efficiency need to be employed. Existing methods, which measure one aspect at a time and focus either on monetary values or on biophysical issues are unsuitable (Cuadra and Björklund, 2007). Ecological values, e.g. generation of ecosystem services, are often not considered at all due to lack of reliable and comparable measurements (Björklund and Rydberg, 2003).

There is currently a lack of assessment methods that relate resource use to the total outcome of an agricultural activity; that evaluate the efficiency of the production (including food products) as well the generation of cultural and natural services and values; and that distinguish between local/purchased and renewable/non-renewable resources. Such assessment methods must have system boundaries wide enough in time and space to provide a basis for constructive dialogue and informed decisions on changes.

The present study combined existing assessment methods such as emergy analysis (Odum, 1996) and ecological footprinting (Wackernagel and Rees, 1996). Emergy analysis accounts for the energy intensity embodied in products, including the environmental work and the work of humans in generating products and services, while ecological footprinting presents the resource use on an area basis. Combining these methods can allow the total resource use on a farm and the part that is local and renewable to be determined.

The classification of ecosystem services in the Millennium Ecosystem Assessment (MA) was used here as the basis for ranking multifunctionality and the results were expressed in the form of ecosystem bundles (see e.g. (Foley et al., 2005)). Assessing the multifunctionality of the farm produced a more perceptive measurement of the efficiency of resource use than if we had assigned the resource use only to the production of e.g. milk or meat.

The overall aim of the study was to develop a useful tool to assess whether changes implemented at farm level to reduce the dependence on fossil fuel-based inputs and the associated impact on global warming actually do so in a longer and broader perspective. The study compared the current production mode on an organic dairy farm with scenarios of alternative production modes with different degrees of intensity in external inputs and milk yields. Specific objectives were to obtain knowledge on options to reduce fossil fuel use and the impact on global warming and to contribute to the development of multi-criteria assessment tools.

The multi-criteria method and the research question: *"How do we know that what we are doing is actually leading to more efficient resource use and is employing more local ecosystem services?"* were formulated by a participatory research group in Sweden comprising farmers and researchers.

Materials and methods

The study was performed on an organic dairy farm (A), with three scenarios for alternative production strategies: Organic milk production maximising self-sufficiency in feed and energy (B); Organic production maximising milk yields (C); and Conventional production maximising milk yields (D) (Table 1).

The study was carried out in 2007-2009 as part of a participatory research project involving 11 farmers on eight certified organic farms in central Sweden, a researcher from the Swedish University of Agricultural Sciences and a process facilitator. The project sought to identify and communicate ways to develop sustainable and fair farming systems based on local ecosystem resources and services. Important aspects of the work were the joint learning process and helping to inspire and open up opportunities to talk about agricultural sustainability with other farmers, consumers and decision-makers. On the basis of research results combined with their practical experiences, the group of farmers helped develop useful tools and methods for assessment.

Description of the farm and the three production scenarios

A) The study farm and its existing production system

The farm Hulta Norrgård is situated in a mainly forested small-scale mosaic area at the edge of agricultural plains, about 20 km south of the city of Linköping in south-east Sweden. The farm is organically certified, with dairy production as the main enterprise. The farm comprises 70 ha of arable land and grazing, and field size is on average 0.5 ha. The animal herd consists of 18 dairy cows, 25 sheep, a few hens and ducks, one dog used to herd the animals out to pasture, and some cats. The animals provide the basis for nutrient recycling of the farm, and the majority (97%) of the animal feed is produced on the farm (Table 1). The farm also includes 30 ha of forest, that were not included in the study although a few hectares of this forest are sometimes used as pasture for cows. The milk production is around 7000 kg per cow and year. The farmer and his wife work full-time on the farm.

The production strategy on the farm is to minimise external resource use so as to become resource-efficient, keep costs low and achieve adequate profitability. Some purchased feeds, seeds and diesel are brought into the farm. The machinery is old and if it breaks down, it is repaired on the farm.

The farm is a node in the local recycling association and it collects and uses the urine and faeces from half the approx. 45 households in the three villages that comprise the association. The association, which has been in operation for 14 years, takes local recycling and local food as the starting-point for rural development. In a small shop on the farm, villagers can sell and buy local products, such as eggs, milk, honey and furs, as well as some fair-traded imported products. Among other things, the farm also provides and prepares land for common cultivation of potatoes and organises hay-making on old meadow in an annual festival.

Scenarios for alternative production modes:

B) Organic dairy production maximising self-sufficiency in feed and energy

In this scenario, all animal feed is produced on the farm. The feed concentrate used is rapeseed cake produced on the farm. The rapeseed oil is used as fuel for the tractors. The cows are mainly fed on grass-clover silage and hay. The size of the dairy herd remains the same (18 cows), but milk production has declined to 6 000 kg per cow and year. Sheep, hens and ducks are kept as today. All land is used, arable land as well as natural pastures and meadows. The sale of local products, e.g. milk and eggs, has been increased and contributes to the farm economy. Wind electricity is produced on-farm to meet the energy demands of the farm.

The strategy is to minimise purchased inputs as much as possible. Food for the family is also produced on the farm: Cereals for own consumption are processed in a small mill, vegetables are grown, and eggs and meat are produced. There is as little machinery as possible and the machines are old and kept repaired on the farm. Two people work full-time on the farm and the cash withdrawals are low.

Local recycling is strengthened and crop seeds are produced on-farm and exchanged with neighbours.

C) Organic production maximising milk yields

The dairy herd is more than doubled, to 40 cows. The majority of the fodder is purchased in, including all feed concentrate and a large proportion of the grain. The most distant pastures and the smallest fields are abandoned. Sheep and poultry are not kept. Dairy production is optimised to give as high milk yields as possible, while still conforming to the rules for organic certification. Silage and hay comprise 60% (by weight) of the feed on an annual basis. Animals are mainly fed indoors year around, with only a small proportion of their diet coming from pastures near the animal house. Milk production is around 9 000 kg per cow and year.

The strategy is to increase the profitability of the farm, both by having high milk production and by adding value to the production by being organically certified. Machinery is modern and investments are made in labour-saving techniques. One person works full-time, hired labour is used for relief milking.

There is no selling of local products, but local recycling of nutrients from households to the farm continues.

D) Conventional production maximising milk yields

The dairy herd is increased to 64 cows, which is the maximum amount in terms of stocking density regulations on the area required for manure application. Only milking cows are kept on the farm, with recruitment leased out to a farm specialising in dairy heifer production. Animals are fed indoors during milking all year around. Only 10 hectares of land near the animal house are used to meet Swedish regulations on the period of outdoor grazing provided for dairy cows. No natural pastures are maintained as the grass contains inadequate concentrations of nutrients to act as feed for high-milking cows. All feeds except grass silage and hay are bought. Fertiliser, herbicides, pesticides and fungicides are used regularly. Milk production is around 10 000 kg per cow and year.

The strategy is to increase the profits from the farm, e.g. by decreasing labour costs and increasing income. One person works full-time on the farm. Hired labour is used for relief milking at week-ends on a regular basis. The machinery is modern and the animal house and milking parlour are easy to work in.

There is no local recycling of nutrients as there is no perceived economic, ecological or social incentive for this and it would only increase the work load.

Table 1. Some data on current production of the organic dairy farm studied (A) and the three alternative scenarios (C-D), all comprising different modes of dairy production.

	A. Current production	B. Low-input organic production	C. Organic production, high yield	D. Conventional production, high yield
Agricultural land (ha)	70	70	70	70
Arable land (ha)	40	40	30	30
Ley on arable land	30	30	30	30
Managed natural grazing (ha)	30	30	10	0
Fallow	0	0	30	40
Average field size (ha)	0.5	0.5	2	2
Milking cows (number)	18	18	40	64
Animal units (number/ha)	0.88	0.88	1.33	1.6
Sheep (number)	25	25	0	0
Milk production (kg cow/yr)	7 000	6 000	9 000	10 000
Rate of own supply of feed (%)	97	100	50	10
Fertilisers	No	No	No	Yes, some
Pesticides	No	No	No	Yes
Financial turnover (Euro/yr)	70 000	50 000	150 000	250 000

Emergy-based footprint

Emergy analysis accounts for the energy intensity embodied in products, including the environmental work and the work of humans in generating products and services. All items are converted to a common basis of solar energy (the unit solar emjoules (sej)) using conversion coefficients (transformities). The transformity is the solar energy used to make one joule of a resource (Odum, 1996). The method has been comprehensively described by a number of authors (Björklund, 2000; Brown and Herendeen, 1996; Odum, 1996).

Emergy analysis has been used in this study to assess and compare resource of different kinds, such as the use of fossil fuels, of iron and of energy in rain. With the emergy analysis it has been possible to put all different resources on a common basis, of the amount of work of environment (the solar energy used) to generate them, and make a comparison that is consistent. By using emergy analysis all resources was possible to include in the same analysis.

To account for emergy in purchased goods, both the emergy input from the environment to generate the raw material and the emergy in human services to make the raw material useful in the economic system were calculated. Emergy in service was calculated from the average emergy flow per unit money flow for Sweden (Lagerberg et al., 1999). Emergy caused by resource use related farmers own labour were omitted in all calculations, due to difficulties in relating economic withdrawal and farm labour.

To facilitate informed discussion, the emergy use was converted to area by dividing it by annual renewable emergy inflow per m^2 (approximately 5.70×10^{10} sej m^{-2} yr^{-2}, which was the contribution from rain). In this way, an indirect area demand was calculated for all purchased inputs. This allowed comparison of the direct and indirect area demand for the different systems. We called this approach the 'emergy-based footprint', and it corresponded to the theoretical area needed if all resources used on the farm were local, renewable resources. This has the same conceptual basis as the ecological footprint developed by Wackernagel and Rees, but the system boundaries are larger and the calculations are based on energy flows, while the Wackernagel and Rees method calculates biological production (Odum, 1996; Wackernagel and Rees, 1996).

Bundles of ecosystem services

Multifunctionality was assessed as the kind and amount of generation of ecosystem services, adopting the classification of ecosystem services used in the Millennium Ecosystem Assessment (MA) (Millennium Ecosystem Assessment, 2005). Ecosystem services are absolutely vital for human civilisations and can be defined as "…conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life (Daily, 1997).

A ranking tool was developed to assess the generation of the services and the results were described in the form of bundles of ecosystem services (see e.g. (Foley et al., 2005; The Resilience Alliance)). Ten people, including the farm family (regarded as one individual), two agricultural researchers and seven farmers, were asked to use short descriptions to rank their opinion of the potential for generation of ecosystem services on a scale from 1 (the lowest ranking) to 5 (the highest) for the farm and the three alternative production scenarios. Weighted averages were then calculated for each service. Eight services, two from each of the four main classifications of MA (provisioning, supporting, regulating, cultural), were depicted in the bundle. The two chosen were important services in relation to agriculture, while also being perceived as representative for that class. Each individual ecosystem service was named according to the MA system as far as possible, but due to the focus of the study, names were modified or services subdivided to be more specific when appropriate. However, the ranking for the provisioning service (milk production) was assessed by the actual milk yield estimated in the scenario, based on diet. The perceived greatest potential of an agro-ecosystem to generate a specific ecosystem service was used as a reference point for the ranking.

Results

Assessment of resource use

The emergy-based footprint, describing the total area needed when all resources used in milk production were produced locally, ranged from 3 times the actual farm area (option B, organic high self-sufficiency) to 14 times that area (C, conventional high yielding) (Fig. 1). In the current production system (A), the total footprint was 4 times the actual farm area. The local resource use was considered renewable as no non-renewable resources such as peat were used, soil organic carbon was maintained at a stable level and there were no signs of soil erosion. Not surprisingly, the local renewable resource use decreased with decreasing self-sufficiency (31% in option B, which maximised self-sufficiency; 24% in the current system A; 11% in option C, which maximised organic milk yield; and 7% in option D, which maximised conventional milk yield).

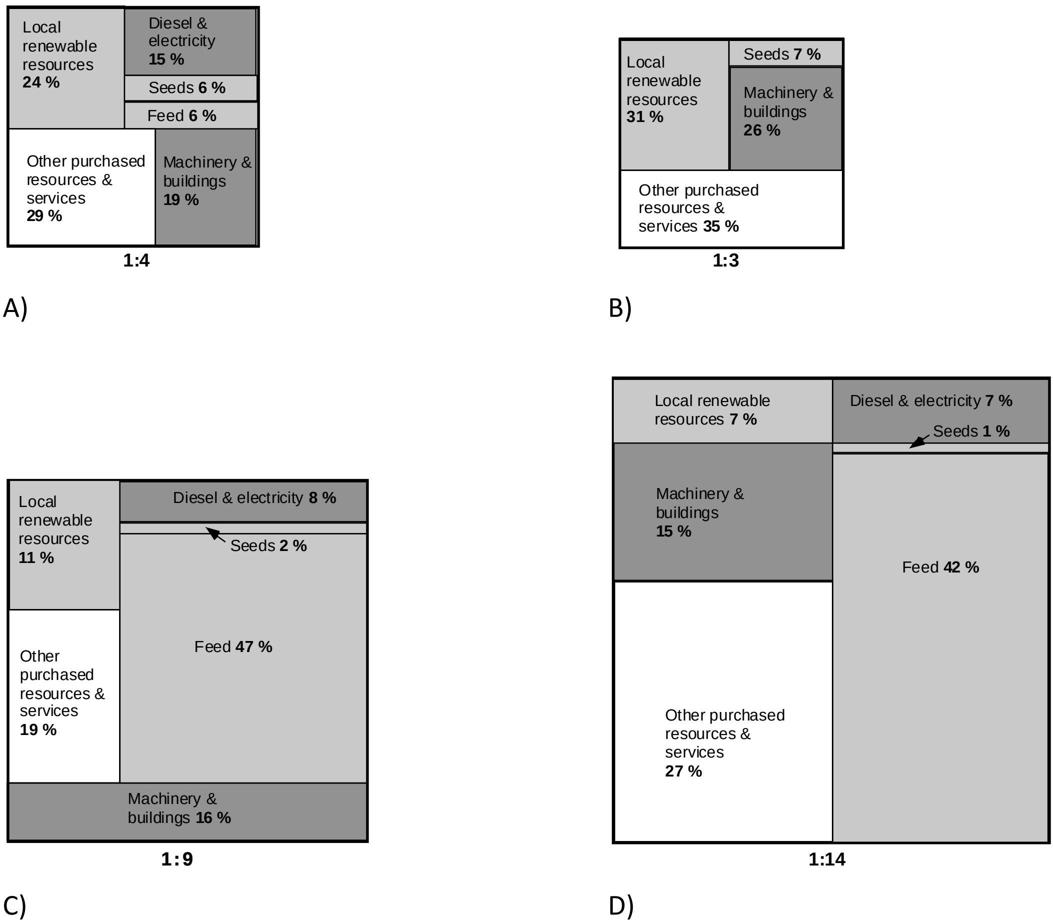

Figure 1. Emergy-based footprint for the current production system (A) and for three alternative production scenarios: B) Low-input organic production, C) Organic production maximising yield and D) Conventional production maximising yield. The ratios below each picture show the local renewable resource use, which is the actual agricultural land area comprising the farm, to total resource use for the production. The agricultural land is similar for all production alternatives (local renewable resources) but differs I proportion to all other resource use.

Purchased feed accounted for the largest resource use in the scenarios where milk production was maximised, (47% in the organic option (C) and 42% in the conventional (D)). In the scenarios with a high degree of self-sufficiency, the greatest resource use was purchased services (other resource use covered by money flows) e.g. veterinary costs, interest and insurances (29% in current production (A) and 36% in the option maximising self-sufficiency (B)).

The proportion of resources from machinery and buildings decreased as milk production per cow increased (26% in the option maximising self-sufficiency (B), 19% in current production (A), 16% in the system maximising organic milk yield (C) and 15% in the option maximising conventional milk yield (D).

Lagerberg et al. (1999) estimated the average renewable part of the resources driving the Swedish economy to be 13% of total resources used. Using that figure, the proportion of the resource use in our scenarios that could be considered renewable (although not only local, as it also included purchased resources) ranged from 35% in current production (A) to 50% for the scenario maximising organic milk yield (C). For the conventional scenario (D), the renewable part was 37%, while for the scenario maximising self-sufficiency (B) it was 40%.

Assessment of the output of the farm – the multifunctionality

The illustration of the multifunctionality obtained by ranking the generation of ecosystem services in the different scenarios indicated that high milk production conflicts with the generation of other ecosystem services.

The current production system received a high ranking in all MA classes, ranging from 4.3 for cultural services to 3.2 for provisioning services (Fig. 2A). Nutrient recycling and soil fertility were the individual services that scored highest, 4.4 and 4.3 respectively, while milk production and contribution to climate regulation got the lowest scores, 1.0 and 3.6 respectively. The picture was similar for the scenario maximising self-sufficiency (B), with a ranking of 4.8 for nutrient recycling and only 0.8 for milk production (Fig. 2B).

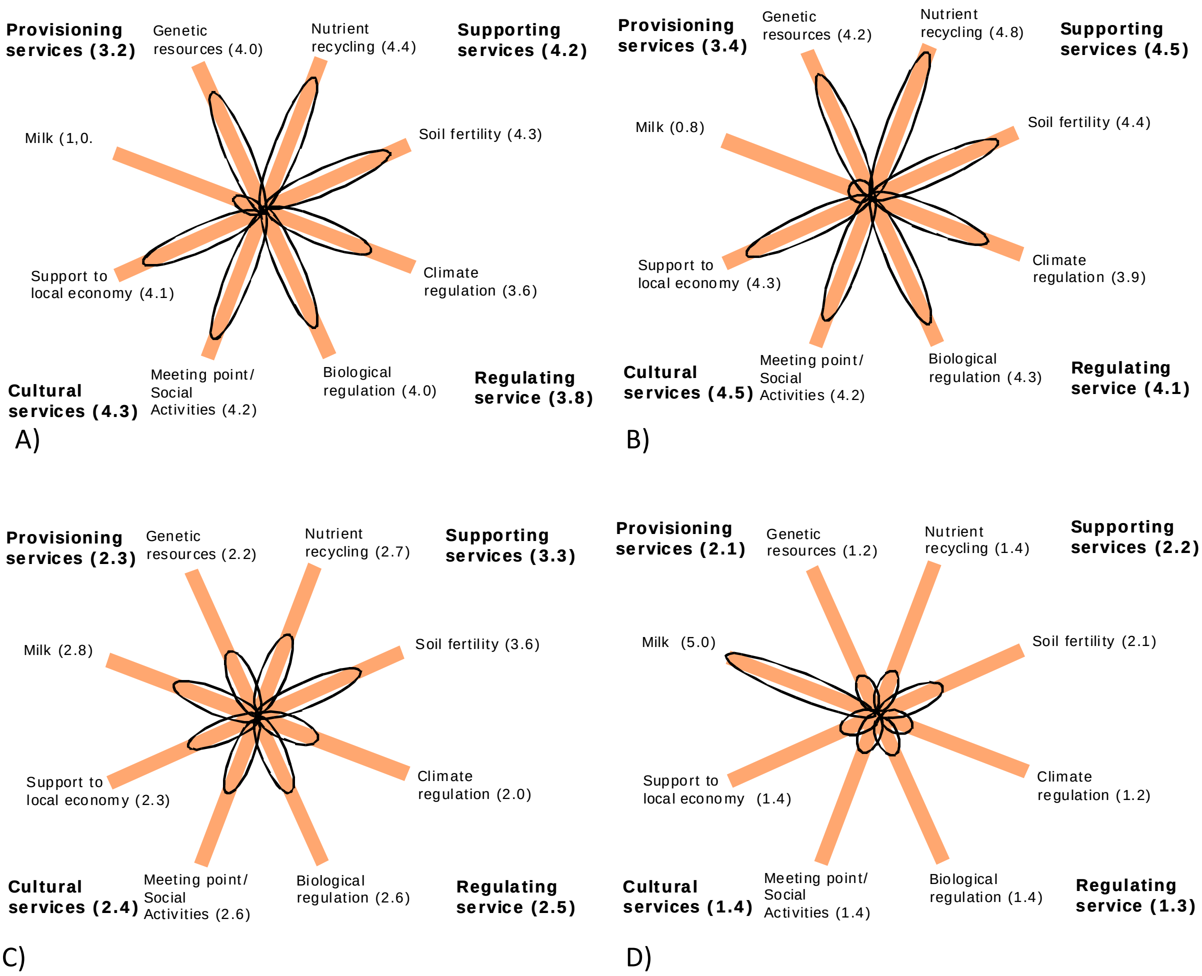

Figure 2. Assessment of generation of ecosystem services for the current production system (A) and for three alternative production scenarios: B) Low-input organic production, C) Organic production maximising yield and D) Conventional production maximising yield. Classification system in the Millennium Ecosystem Assessment was used as basis for the assessment, which was done as a ranking exercise by farmers and researchers individually on basis of mainly written information about the farm and the scenarios constructed. Figures in parenthesis are weighted averages of rankings of the certain services as well as of the all services in the different classes.

For the scenarios maximising milk yields the situation was reversed, with high scores for milk production, 5.0 for conventional production (D) and 2.8 for organic (C) (Fig. 2D and 2C). For the organic option, however, soil fertility got the highest ranking, 3.6. The contribution to the generation of genetic resources, wild and domestic, was ranked lowest (1.2) for the conventional production option, while the contribution to climate regulation was lowest (2.0) for the organic production option.

When the average scores for all four classes were added up for the four scenarios, that maximising self-sufficiency (B) received the highest score of 16.5, the current production system (A) scored 15.5, the system maximising organic milk production (C) scored 10.5 and that maximising milk conventional production scored 7.0.

Discussion

In the present study, the degree of self-sufficiency seemed to have a larger impact on the size of the emergy-based footprint than whether the production was organic or conventional. Purchased feed was the item making the largest contribution to the footprint when milk production was maximised.

The total size of the footprint did not differ substantially when the production was organic when the strategy was to maximise milk production (Fig. 1C and 1D). However the share of the resource use that was estimated to be renewable, local and not local (results not shown) was higher when production was organic. In the scenario where organic milk production was maximised, this share was the highest for all four scenarios. The reason was a large proportion of renewable resources in purchased feed.

Even when the multifunctionality of the production was considered and expressed in ecosystem bundles, the differences were larger between the scenarios with high and low self-sufficiency than between organic and conventional.

The high ranking of nutrient recycling for the scenarios with high self-sufficiency (Fig. 2A and 2B) was obviously due to no or nearly no purchased feed and recycling of sewage from neighbouring households. Local selling of milk was also highest in option B.

A reason why the scenario maximising organic milk production (C) scored higher than that maximising conventional milk production (D) for soil fertility, even though the area of ley production was similar, may be the common use of a larger number of different sorts and varieties of ley species including clover (Trifolium) in organic agriculture than in conventional. Fields with high biodiversity have been shown in field trials to have a higher potential to build-in soil carbon than fields with lower, even when yields are similar (Steinbeiss et al., 2008). This may refer also to the capacity to contribute to climate regulation, which accordingly was ranked higher for the organic scenarios.

A conceivable argument for the higher ranking of the potential for maintenance of genetic resources, wild and domestic, and for biological regulation for the scenarios with high self-sufficiency and lower production intensity is that the habitat variety increases when the area is maintained with lesser intensity. Moreover, the habitat diversity is larger e.g. when a cropping sequence includes cereals, legumes, oilseeds and ley than only one of these crops, as in the scenarios maximising milk production (leys in this study). High habitat diversity is suggested to be one of the main factors producing potential for high biological diversity in agriculture (Benton et al., 2003). In contrast, high intensity in production (measured as harvested yields) has been found to reduce the biodiversity (Donald et al., 2006). An obvious reason for the low score for strongly biodiversity-related services in conventional production is the use of herbicides and pesticides. Moreover, old breeds of animals and varieties of crops are also maintained to a higher degree in alternatives with a high degree of self-sufficiency, as they have been shown to be more resilient and yield better when soil nutritional levels are low and variable (Araya and Edwards, 2006; Ong´wen and Wright, 2007).

Selling produce locally and the involvement in the local recycling association contributed to local economy and at the same time provided more space and motivation for social activities in relation to the farm in the scenarios with the strategy of high self-sufficiency compared with the scenarios with a strategy to maximise milk production.

When the average ranking of ecosystem services for all classes was calculated, the scenarios with high self-sufficiency achieved the highest values. This may indicate that they are the most multifunctional production systems. However, the final value masks the fact that the ranking is relative and that some services may be more vital than others in a global or local sense and during different times. A high score in that case would depend on the ability of other areas to provide the specific service and also what is most urgent to consider at that time. Two obvious examples are milk production if people are starving locally or globally, and climate regulation when emissions are too high in society in general. Changing perspective from an anthropocentric to an ecocentric focus may also shift the value of the different services.

The perceptions of persons performing the rankings, which were based on their knowledge of the systems and their former experiences, as well as what they consider to be the reference points, had a large impact of the results. Assessments by a large group of people from different fields would have made the ranking more reliable. The choice of individual ecosystem services or functions presented form the ranking was also crucial for the results presented.

Finally, the construction of the scenarios and the estimates of resource use made for calculation of the emergy-based footprint were found to be crucial for the results. A sensitivity analysis would have made the results more reliable. In spite of this, the participatory research group found that this multi-criteria method provided information to deepen the discussion on what a future sustainable agricultural system would look like. The method was perceived as well worth further development and application in other assessments.

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