Journal of

Agriculture Policy

(JAP)

CARI Journals

Journal of Agricultural Policy
ISSN 2520-7548 (Online)
Vol.3, Issue No.1, Pp 75- , 2020 www.carijournals.org

REVIEW OF TWENTY YEARS OF ECOSYSTEM SERVICES RESEARCH AT HENFAES SILVOPASTORAL NATIONAL NETWORK EXPERIMENT

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Abstract

Purpose*:* This study systematically reviewed and synthesised all the scientific literature that has so far been conducted on the ecosystem services of the UK's Silvopastoral National Network Experiment, the Henfaes Silvopastoral Systems Experimental Farm of Bangor University, Wales, and other studies in temperate Europe from 1988 to 2012 to establish what has been done to date, the benefits and contributions to our knowledge base, and potential knowledge gaps and priorities for future research.

Methodology*:* All available papers and grey literatures, since the inception of the UK's Silvopastoral National Network Experiment in 1988, were extracted and reviewed primarily by accessing various electronic databases and existing library collections. The research papers were split into peer-reviewed (published) and non-peer-reviewed (unpublished) papers. The ecosystem services framework was used to relate the four major categories of ecosystem services (provisioning, regulating, cultural and supporting) to the scientific domain of the research studies. The scientific domains addressed include timber or wood-fuel potential, pasture/livestock management, carbon sequestration, soil improvement, water management, and biodiversity enhancement.

Findings*:* Results show that 66 research studies were conducted over the 20-year study period on ecosystem services of which 45% were produced based on studies at Henfaes Silvopastoral Systems Experimental Farm, 32% at UK's Silvopastoral National Network Experiment, 12% were from other silvopastoral systems trials in the UK, and 11% were from European-wide silvopastoral systems studies. The trendline indicated that the number of annual studies on ecosystem services were greatest in the mid and late 1990s than in any other time over the 20-year study period. The studied ecosystem services dealt with provisioning services (40%), regulating services (13%), and supporting services (47%). The scientific domains addressed include timber or wood-fuel potential (20%), pasture/livestock management (20%), biodiversity (20%), carbon sequestration (13%), water management (15%), and soils (12%).

Unique contribution to theory, practice and policy*:* It is hoped that the results of this study will lead to better understanding of the economic and environmental implications of silvopastoral system, and hence generate more attention towards accelerating its adoption and institutionalization in national rural development policies.

Keywords: *agroforestry, silvopasture, timber, pasture, livestock, carbon sequestration, soils, water, biodiversity.*

INTRODUCTION

The UK's Silvopastoral National Network Experiment (SNNE) was set up with a view to studying the potential of silvopastoral agroforestry on UK farms (Sibbald and Sinclair, 1990). Over the past two decades (1992-2012), much of the on-farm and on-station research efforts have involved detailed studies of ecological and physical processes, primarily for the purpose of establishing a solid knowledge base on the functions and capabilities of silvopastoral agroforestry. However, no attempt has been made to date to synthesise and publicise this knowledge and this has led to a lack of appreciation of the environmental and economic benefits of this land-use system.

This study provides an overview of the state of current knowledge of ecosystem services of the UK's Silvopastoral National Network Experiment (SNNE) with specific focus on the Henfaes Silvopastoral Systems Experimental Farm (SSEF) of Bangor University, North Wales, United Kingdom. Other studies in the UK as well as in temperate Europe with similar environmental conditions to the UK are also included in this review.

The study is based on a systematic review and synthesis of all the scientific literature that has so far been conducted on this topic from 1988 to 2012 using the ecosystem service framework. The paper evaluates the status of the research in the farm's ecological and physical processes to establish what has been done to date, the benefits and contributions to our knowledge base, and potential knowledge gaps and priorities for future research, from the data of ecosystem services in silvopastoral agroforestry systems.

It is hoped that this review and synthesis of the ecosystem service issues addressed by the UK's SNNE, Henfaes SSEF and other studies in temperate Europe, along with the variables and nature of the studies, will bring to the fore the knowledge that would undoubtedly lead to better understanding of the economic and environmental implications of silvopastoral system, and hence more attention being paid to accelerating its adoption and institutionalization in national rural development policies.

MATERIAL AND METHODS

Information sources considered

In order to appraise the current status of research studies on silvopastoral systems with respect to the ecosystem services framework, all available papers, published and unpublished since the inception of the UK's SNNE in 1988 were reviewed. The screening and compilation of available, peer-reviewed, and non-peer-reviewed research papers were made primarily by accessing various electronic databases and existing library collections.

Specific sources include databases maintained by the Bangor University libraries; the School of Environment, Natural Resources and Geography, Bangor University; UK's Farm Woodland Forum; World Agroforestry Centre (formerly ICRAF); and the Food and Agriculture Organisation of the United Nation (FAO). Furthermore, there was scanning of the titles of the journals of *Agroforestry Systems*, *Agroforestry Abstracts*, *Agroforestry Today*, *Agroforestry Forum*, and conference proceedings.

In order to ensure that all research that has been carried out was reviewed, further investigation was undertaken to extract additional relevant publications and grey literatures. Since the Henfaes's SSEF serves as an outdoor laboratory for Bangor University research students, restricting the review to only peer-reviewed articles would have missed many important contributions made to the field by these students who have produced many theses on the experimental farm. Therefore, by using both peer-reviewed and non-peer reviewed research outputs this paper examines what has been accomplished, what major questions have been addressed so far.

Classification of research papers

Journal of Agricultural Policy
ISSN 2520-7548 (Online)
Vol.3, Issue No.1, Pp 75- , 2020

To facilitate analysis and synthesis, the research papers were classified according to the following criteria:

1. Thematic groups: The research papers were split into two major thematic groupings: peer-reviewed (published) and non-peer-reviewed (unpublished student theses) papers.
2. Ecosystem service functions addressed: research papers were further categorised into ecosystem service function groups in relation to the following economic and environmental benefits of silvopastoral systems:

   - Timber or fuel potential
   - Carbon sequestration
   - Pasture/Livestock management
   - Soil improvement
   - Water management, and
   - Biodiversity enhancement

RESULTS AND DISCUSSION

Overall, the following results and discussion use the ecosystem services framework and relate the four major categories of ecosystem services (provisioning, regulating, cultural and supporting) identified by the UK National Ecosystem Assessment (2011) and the Millennium Ecosystem Assessment (2005) to the scientific domain of the research studies.

What has been done to date

The trend line, Figure 1 below, shows that greater number of annual studies on ecosystem services of the UK's Silvopastoral National Network Experiment and temperate Europe were conducted in the mid and late 1990s than in any other time over the 20-year study period. Interest in the topic remained generally minimal in the early 1990s and from 2001 to the end of the decade. However, there is indication of rising trend in academic involvement thereafter.

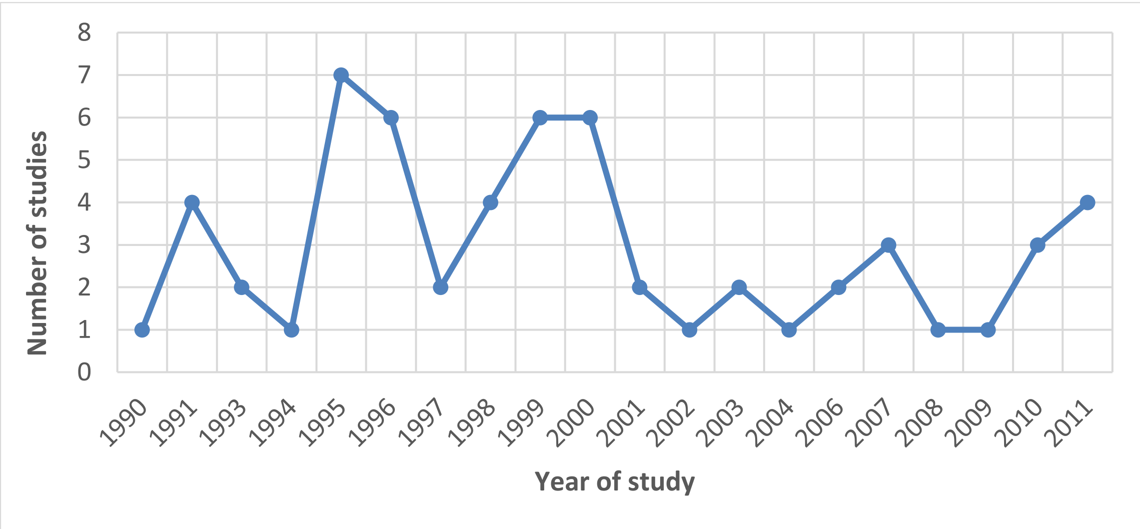

Figure 1. Number of identified scientific literature since 1988 on ecosystem services of the UK's Silvopastoral National Network Experiment and temperate Europe

Ecosystem services categories within different ecosystem systems services of silvopastoral systems trials are shown (Table 1, Figure 2 and Appendix 1), giving an overview on the major research question: What has been done to date?

Results of the categorisation of the research papers show that 66 research studies have been conducted since 1988 on ecosystem services of the UK's SNNE and temperate Europe (Table 1 and Appendix 1). Thirty (45%) of the 66 studies were produced based on studies at Henfaes SSEF, twenty-one (32%) at UK's SNNE, eight (12%) were from other silvopastoral systems trials in the UK, and seven (11%) were from European-wide silvopastoral systems studies. These 66 research studies are split into peer-reviewed (published) and non-peer-reviewed (unpublished) papers. 31 (47%) of these studies were classified as peer-reviewed, and 35 (53%) as non-peer-reviewed. The 35 non-peer-reviewed studies included 1 PhD thesis, 1 MPhil thesis, 20 MSc theses and 2 BSc theses at Bangor University and the rest 11 are information in various newsletters of the UK's SNNE. Only 2 BSc theses of Bangor University were included in this review because they were the only ones considered reliable and they were authenticated by the academic staff of the School of Environment, Natural Resources and Geography, Bangor University, Wales.

Table 1: Category of Research studies Reviewed

TYPE OF PAPER	Research site				TOTAL 1988-2012
	Henfaes SSEF	UK's SNNE	Other UK	Other Europe	
Peer- Reviewed	6	10	8	7	**31**
Non-Peer-Reviewed	24	11	0	0	**35**
TOTAL	**30**	**21**	**8**	**7**	**66**

Figure 2 shows the frequency of the different ecosystem services appearing in the 66 research studies and their share in ecosystem service categories. In all, 3 ecosystem service categories and 6 different ecosystem service scientific domains have been studied. In general, 40 percent of the studied ecosystem service categories dealt with provisioning services, 13 percent with regulating services, and 47 percent with supporting services. However, the ecosystem service category of cultural service is yet to be studied. The most common ecosystem service scientific domains assessed in the sample are timber or wood-fuel potential (13 studies or 20%), pasture/livestock management (13 studies or 20%) and biodiversity enhancement (13 studies or 20%). Other ecosystem service domains studied include carbon sequestration (9 studies or 13%), soil improvement (8 studies or 12%), and water management (10 studies or 15%). It is not unusual to address more than one ecosystem service domain in a study (Figure 2 and Appendix 1).

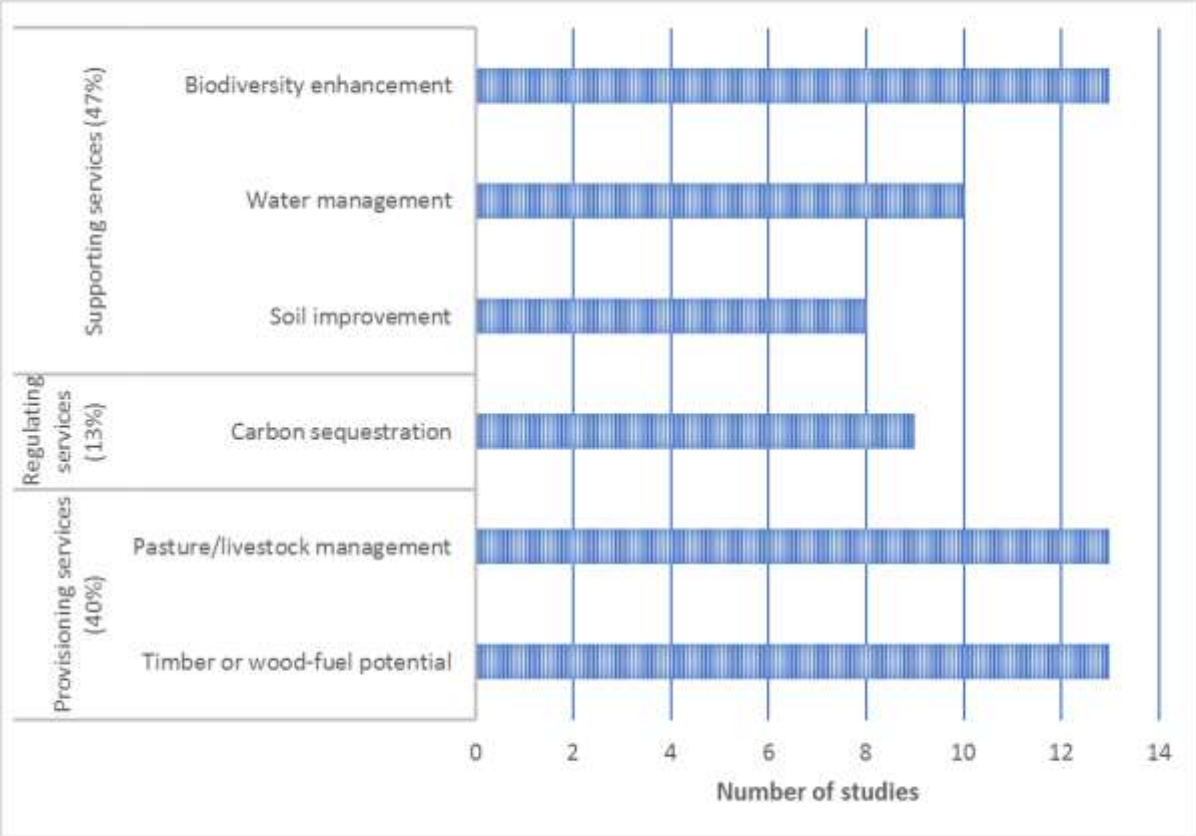

Figure 2. Frequency of the different ecosystem service domains appearing in the 66 publications and their share (%) in ecosystem service categories

The strength of linkages between categories of ecosystem service functions and components of scientific domain are illustrated in Figure 3. The scientific domain has multiple constituents including Tree, pasture and livestock productivity; Tree growth, form, phenology & wood properties; Carbon stock estimation; Water relation; Diversity of fauna; Nutrient composition and storage; Nitrogen-fixation & Nitrogenase activities; and Soil enrichment.

Arrow Width - intensity of linkages between scientific domain and key ecosystem service functions:

8 points

7 points

6 points

5 points

3 points

2 points

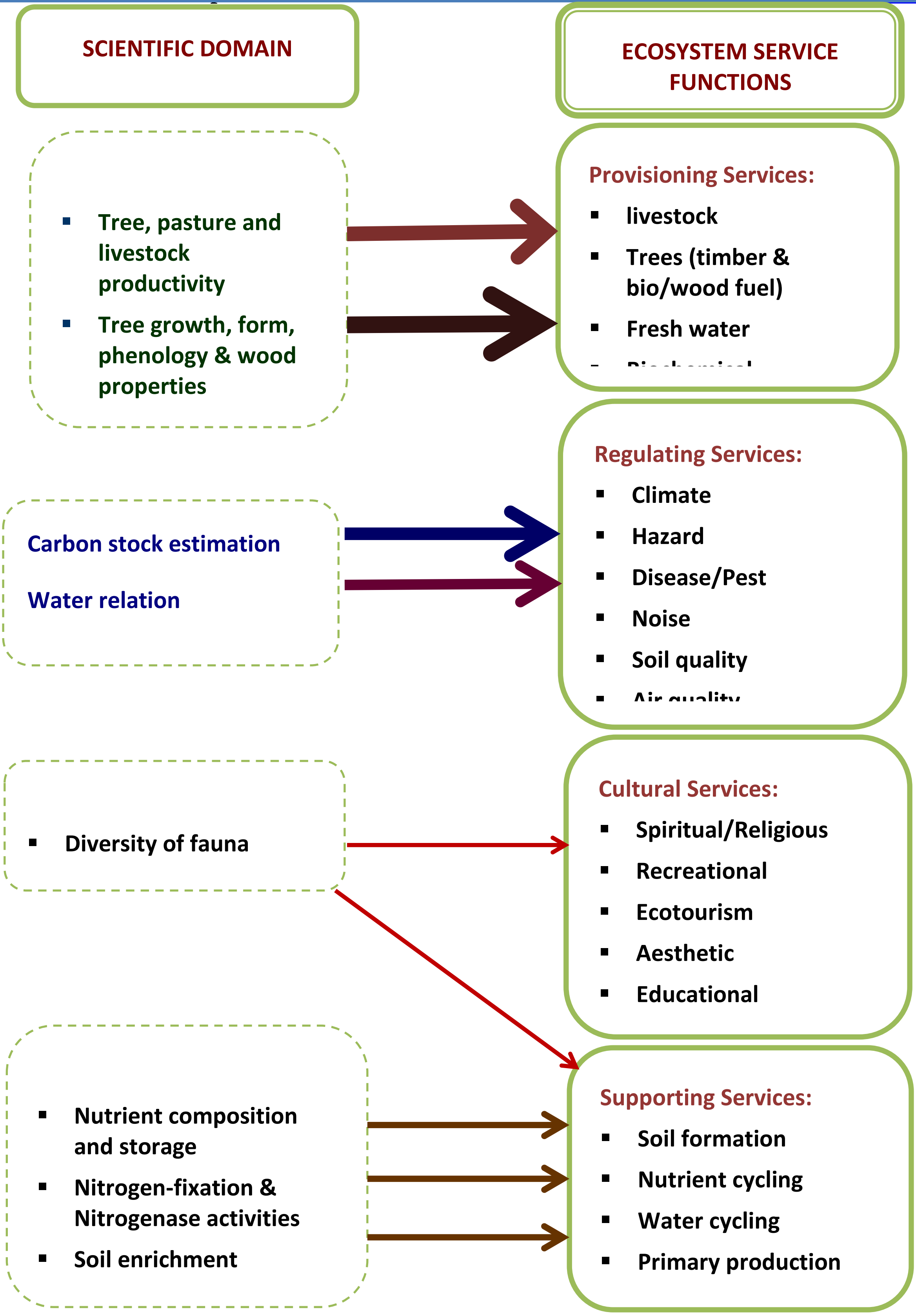

Figure 3: Linkages between Ecosystem Services and Research Scientific Domain

Benefits and contributions to knowledge base

This section presents the results of the review on the benefits of silvopastoral agroforestry systems in relation to: timber or fuel potential, livestock management, carbon sequestration, water management, soil improvement, and biodiversity enhancement. In general, the discussion below cuts across the four major categories of ecosystem services (provisioning, regulating, cultural and supporting) identified by the Millennium Ecosystem Assessment (2005) and the UK National Ecosystem Assessment (2011).

Timber or fuel potential

Silvopastoral systems are designed to produce either timber or firewood, while providing intermediate cash flow from the livestock component. The potential of growing timber or firewood species into pasture was investigated in the UK since 1988 as part of UK's SNNE. Sibbald *et al*. (2001) provided results of the performance of timber trees for the first six years (establishment phase) of the UK silvopastoral national network experiment. There were no significant differences in tree survival between the silvopastoral treatments and woodland control (mean 92.5% ± 0.74). By year six, woodland control and trees at 100 stems ha^{-1} were similar (180.7 ± 17.31 cm) while trees at 400 stems ha^{-1} were taller (219.0 ± 22.80 cm: $p < 0.05$). It was concluded that tree shelters maintained silvopastoral tree survival at the level of conventional woodland. Tree height extension was, however, compromised on 100 stems ha^{-1} plots where a higher animal: tree ratio resulted in greater animal activity and soil compaction around trees compared to 400 stems ha^{-1} (Sibbald *et al*., 2001).

Tree performance in relation to tree density and planting configuration in a silvopastoral system was also investigated at Henfaes SSEF by Roberts (1995), Englund (1995), Winslade (1996), Howe (1997), Ng'atigwa (1997), Zapater (1998), Gerety (1998), Islam (2000), Teklehaimanot *et al*. (2002), and Mmolotsi and Teklehaimanot (2006). Generally, the results of these studies indicated that tree performance within silvopastoral treatments was better at the higher planting density (400 stems ha^{-1}) and in silvopastoral plots with trees planted in clumped pattern. Stem diameter and tree height, which are indicators for tree growth, were generally better for all trees at 400 stems ha^{-1} and for trees planted in clumped pattern, and that alder demonstrated better growth than sycamore. The authors attributed the poor performance of the wider spaced trees (100 stems ha^{-1}) to greater exposure to wind of widely spaced trees (Green *et al*. 1995), and to the effects of animals, either through browsing or soil compaction (Sibbald *et al*., 1995; Sibbald *et al*., 2001; Bezkorowajnyj *et al*., 1993).

The detailed results of the study by Islam (2000), who investigated the effect of spacing, planting pattern and sheep on tree growth, form and phenology of trees at Henfaes SSEF, showed that height and diameter did not vary significantly with treatments in sycamore or red alder seven years after planting. However, there were significant differences in tree form and phenology. A significantly higher height: diameter ratio was found in the woodland control than in the widely spaced 400 stems ha^{-1} treatment in red alder. The number of shoot reiterations per tree (in total and the number of adaptive reiterations) were significantly lower in the woodland control than in two of the widely spaced silvopastoral treatments of both species (100 stem ha^{-1} for sycamore and 400 stems ha^{-1} for red alder) but in red alder the woodland control resulted in a significantly larger number of traumatic reiterations (The development of a shoot with a seedling growth form from the trunk, branch or root of a mature tree as a result of damage) per tree than in the 400 stems ha^{-1} treatment. In red alder, the number of dead branches and the rate of branch mortality were significantly higher in the 400 stems ha^{-1} treatment than in the woodland control. Spacing also had significant effects on different phenological variables of both species. Shorter winter shoot dormancy periods were found in the woodland control than in the 100 stems ha^{-1} treatment in sycamore, and a longer period of leaf production and a shorter winter dormancy period were found in the 400 stems ha^{-1} than in the woodland control in red alder. In red alder, the 400 stems ha^{-1} treatment resulted in a greater number of male catkin clusters and fruit clusters. The author concluded that tree forms were the best in the closely spaced woodland control and the least in the widely spaced silvopastoral treatment of 100 stems ha^{-1} in sycamore. The author associated the poor performance in the 100 stems ha^{-1} treatment with direct effects of animal activity that caused soil compaction and direct damage to the trees (Sibbald *et al*., 1995; Sibbald *et al*., 2001). The effect of livestock on soil compaction was also evaluated at Henfaes SSEF by Jarju (2000). Results showed that there was significant difference between treatments in soil compaction ($P < 0.001$). The highest mean penetrometer pressure weight was recorded at sycamore 100 stems ha^{-1} (66.23 kg) followed by 56.70 kg and 57.15 kg in 400 stem ha^{-1} alder and sycamore treatment plots, respectively.

Mmolotsi and Teklehaimanot (2006) assessed the timber and wood-fuel properties of red alder and sycamore at Henfaes SSEF. They found that tree-planting density had no significant effect on wood density and modulus of rupture in both tree species. However, tree-planting density had border line significant effects ($p<0.05$) on the modulus of elasticity (MOE) in red alder and compression strength ($p<0.01$) in sycamore. Wood samples taken from red alder in woodland control had a significantly higher MOE than those from trees in low-density plots of 400 stems ha^{-1} (silvopastoral system). Sycamore wood from the woodland control had significantly higher compression strength than that from the 400 stems ha^{-1} (silvopastoral) plots. In general, wood mechanical properties of red alder were found to be significantly different from that of sycamore. Sycamore yielded higher wood density (0.64 g cm^{-3}), modulus of rupture (90.24 MPa) and compression strength (36.49 MPa) than red alder (0.49 g cm^{-3}, 73.48 MPa and 32.13 MPa, respectively). However, modulus of elasticity was higher in red alder (7614.64 MPa) than in sycamore (7430.05 MPa), although it was not significantly different. Based on the results of wood properties of red alder it was concluded that red alder is a medium strength tree species with potential for furniture manufacturing and for ordinary non-structural uses such as paneling and studs.

Planting density did not also have any effect on the wood-fuel higher heating value of either red alder or sycamore. However, red alder wood had a significantly higher fuel-value index (1638) than sycamore (1481), owing to higher ash content of sycamore (Mmolotsi and Teklehaimanot, 2006). Thus, it was concluded that red alder has a potential to provide a better bio-energy than sycamore for heating homes and generating electricity. From these results, it may be concluded that high quality timber and firewood can be produced from silvopastoral systems as most of the wood properties were not affected by planting trees at wide spacing.

As shown by the results of the studies at Henfaes SSEF by Roberts (1995), Englund (1995), Winslade (1996), Howe (1997), Ng'atigwa (1997), Zapater (1998), Gerety (1998), Islam (2000), and Teklehaimanot *et al*. (2002), planting sycamore trees in clumps rather than as individuals resulted in silvicultural advantages due to the proximity of adjacent trees within the clump at the same time as silvopastoral advantages of permitting grazing between the clumps. The clumps required less than half the cost of tree protection of individual trees in widely spaced treatments of 100 and 400 stems ha^{-1}, initial tree growth in clumps was not significantly different from the woodland control and livestock productivity in clumped treatment was not significantly different from the pasture control.

According to McAdam *et al*. (2007a), at year 15, hurley quality ash butts were sold for €1048 ha^{-1} from North Ireland silvopastoral experiment site. Hence, the authors concluded that silvopastoral systems have the potential to support rural wood-based industry.

Because of long rotation period for trees, most estimates concerning the benefits of growing timber in silvopastoral systems are based on computer models. For example, comparing the financial viability of silvopasture system and pasture system, Sibbald (1996) found that the net present value for ash (*Fraxinus excelsior* L.) growing in silvopastoral system in lowland UK was greater than the net present value for treeless pastures by 15%. McAdam *et al*. (1999a) and Thomas and Willis (2000) also found that, under a range of commodity prices and agricultural subsidy support scenarios, silvopasture has a net benefit over open grassland ranging from 34% to 181%. Even with no farm subsidy support, silvopasture was more profitable (by €20 ha^{-1}) than open grassland as the result of the additional output of timber from silvopastoral systems.

There is ample evidence from the high survival and reasonable growth rates of trees in silvopastoral systems that high-quality trees for the purposes of either timber or firewood can be established in grazed pasture in Britain without affecting livestock production for at least the first ten years (Sibbald *et al*., 2001; Teklehaimanot *et al*., 2002). This has important implications because it means, on the one hand, that farmers do not lose annual agricultural income from the land under silvopastoral systems during the establishment period, but on the other, that this type of agroforestry may not necessarily contribute to short-term reductions in surplus agricultural production in the UK as had once been thought (Sheldrick and Auclair, 2000).

Pasture/Livestock management in silvopastoral systems

Silvopastoral systems offer a variety of benefits for livestock management. Silvopastoral systems can affect livestock productivity through mitigating heat or cold stress and by altering understorey pasture growth. Such benefits of silvopastoral systems have been researched in the UK at the UK's SNNE since 1988.

The effect of trees in silvopastoral systems on pasture production, which consequently has effect on livestock production, was studied by Ng'atigwa (1997), Onyeka (1998) and Zapater (1998) at Henfaes SSEF. Results of these studies, in general, indicated that there was no significant difference in pasture production between the silvopastoral and pasture control treatments six years after tree establishment. Sibbald *et al* (1991), based on silvopastoral systems experiment of re-spaced Sitka spruce trees (*Picea sitchensis*) in Glentress forest, Scotland, also found that grass sward growing beneath widely spaced trees, above ground conditions, did not greatly limit rates of herbage production, under trees of up to 8 m in height and at spacing as close as 6 m (about 300 stems ha^{-1}). However, a higher amount of pasture production was obtained from the pasture control without trees than in silvopastoral treatments nine years after tree establishment at Henfaes SSEF (Nghitoolwa, 2001). Thus, the impact of trees on pasture growth and consequently on livestock production in a silvopasture depends on several factors including the forage and tree species used, the age and size of each component, and tree spacing and orientation (Hawke, 1991; Sibbald *et al*., 1991; Teklehaimanot et al., 2002).

Sibbald and Dalziel (2000) reported that, in the UK's SNNE, no significant differences in lamb growth were observed between silvopastoral treatments and the pasture control until up to ten years after establishment of the sites. Results of the research at the silvopastoral system experiment at Henfaes have also shown that there was no significant difference in livestock production between silvopastoral treatments and the pasture control during the first six years of the tree establishment phase (Teklehaimanot *et al*., 2002). Also, a study conducted by Green *et al*. (1995), in a silvopastoral experiment established by re-spacing Sitka spruce (*Picea sitchensis* (Bong.) Carr) plantation in Glentress forest, Scotland to create a silvopastoral system and study the effects of widely spaced trees on the microclimate and consequently on herbage production from sown grass swards (Sibbald *et al*., 1991), showed that widely spaced trees can significantly reduce wind speeds that have impact on livestock production. The trees were re-spaced at intervals of 4, 6 and 8 m by thinning the Sitka spruce trees originally planted at 2 m spacing. Trees also buffer spring and autumn temperatures extending the growing season of pasture in silvopastoral systems (Sibbald *et al*., 1991). These can enhance livestock productivity.

The lack of significant difference in lamb growth rate and livestock carrying capacity between treatments found in UK's SNNE as well as Henfaes SSEF up to ten years after establishment may be explained by the fact that the negative effects of trees on pasture production may have been compensated by the positive shelter effects of trees on livestock (McArthur 1991; Sibbald *et al*., 1991; Ainsworth *et al*., 2012). Once the tree canopy closes, however, pasture production, and thus livestock production could decline. For instance, Hawke (1991) in New Zealand found that lamb live weight gains from perennial ryegrass and white clover (*Trifolium repens* L.) was reduced approximately 50% in 15-year-old radiata pine (*Pinus radiata* D. Don) plantations with 200 stems ha^{-1} compared to pastures without trees. However, this depends, as mentioned above, on the forage and tree species used, the age and size of each component, and tree spacing and orientation. Thus, the positive shelter effects of trees on livestock production as reported above may continue for many years even after tree canopy closes in the UK silvopastoral systems.

In two of the five UK's SNNE trials, one in Scotland and the second in Northern Ireland, it was found that sheep spent more time in the shade and shelter of trees on hot sunny days and cold windy days than they did in the open (Sibbald *et al*., 1995; Hislop and Claridge 2000). This amelioration of conditions could also be a positive welfare benefit to livestock.

Carbon sequestration in silvopastoral systems

Carbon sequestration is an important ecosystem service provided by silvopastoral systems. An interesting recent development in the UK is the increasing recognition of the value of such ecosystem service, in the context of increasing concerns about global climate change, provided by sustainable land management systems such as silvopasture. According to Nair (2012), silvopastoral systems are able to sequester more carbon in soil when compared with silvoarable practices due to accelerated decomposition of soil organic matter following soil tillage done as a soil management practice for crop production in silvoarable systems.

Silvopastoral systems are, therefore, believed to offer a low-cost method to sequester carbon because of their perceived ability for greater capture and utilization of growth resources (light, nutrients, and water) than single-species crop or pasture systems (Pandey, 2002; Montagnini and Nair, 2004). Carbon (C) sequestration is estimated by assessing the C stored both aboveground and in the soil. The estimates of C stored in agroforestry systems, in general, range from 0.29 to 15.21 Mg ha^{-1} yr^{-1} aboveground and 30 to 300 Mg C ha^{-1} down to 1 metre depth in the soil (Pandey, 2002; Montagnini and Nair, 2004). Dixon *et al*. (1994) also evaluated the C sequestration potential of agroforestry and alternative land use practices in 94 nations worldwide and found that the carbon storage values (including below-ground storage) for agroforestry ranged between 12 and 228 Mg C ha^{-1} with a median value of 95 Mg C ha^{-1} and concluded that the potential for C accretion via biomass production is greatest within tropical latitudes. There is, however, limited research investigating the C sequestration potential of silvopastoral systems in temperate Europe.

Studies were carried out at Henfaes SSEF to estimate the C sequestration potential of silvopastoral systems as described below:

Research carried out by Kasahun *et al*. (2011) quantified and compared the amount of C stored under different tree species in silvopastoral systems at Henfaes. The mean Soil Organic Carbon (SOC) content under 19-year-old red alder *(Alnus rubra* Bong.) and sycamore (*Acer pseudoplatanus* L.) were 4.30% and 4.51%, respectively. These values were almost two times higher than the SOC content of the soil under the pasture control (2.06%) that was not integrated with any tree species. The authors concluded that both red alder and sycamore have a positive impact in increasing the C pool potential in silvopastoral systems.

Ramdial (2010) quantified the ecosystem C stocks of sycamore at the age of 18 years planted at different densities at Henfaes SSEF. Ecosystem C significantly increased (p<0.05) with an increase in tree density. Tree biomass C stocks ranged from 7.62 ± 4.28 in 100 stems ha^{-1} to 80.43 ± 1.89 t C ha^{-1} in 2500 stems ha^{-1} (woodland control) while SOC, to a depth of 30 cm, ranged from 202.44 ± 11.78 in 100 stems ha^{-1} to 244.98 ± 8.12 t C ha^{-1} in the woodland control, indicating that a major portion of ecosystem C stocks was stored in the SOC pool. SOC was found to decline with soil depth. Similar values of tree biomass C stocks were also reported by Khanal (2011) who found that tree biomass C stock in woodland control plots (2500 stems ha^{-1}) at Henfaes SSEF was 130.29 ± 6.39 t ha^{-1} which was 10.7 and 6.7 times more than in 100 and 400 stems ha^{-1}, respectively. Model simulations run by Ramdial (2010) using the CO2FIX model showed that reducing thinning volume and extending rotation length increased C stored in tree biomass and soil over the long term but, managing stands for bio-energy provided additional C sequestration benefits.

In another study conducted by Agard (2011) at Henfaes, it was found that hedges have a positive influence on SOC content causing an increase of around 16% above the natural field content closer to the hedge. This result agrees with some of the findings reported by Follain *et al*. (2007) who provided a comprehensive review of authors that substantiate the increases SOC content with the presence of hedges. Also, in another study conducted by Benjamin (2010) on twelve provenances of ash (*Fraxinus excelsior*) planted at Henfaes, the aboveground carbon stocks in the twelve provenances ranged from 188.69 to 208.26 t ha^{-1}. However, there was no statistical difference between provenances in SOC content, which varied from 188.04 to 199.68 t ha^{-1}, but differences were found with increases in soil depth.

Rodwell (2009) conducted a biophysical and economic appraisal of lowland silvopastoral systems in Wales to determine their suitability as carbon sequestration schemes for farmers. The author found that tree planting can increase aboveground biomass, and therefore total carbon sequestered, with increasing planting density. This implies that if carbon sequestration is the primary objective, woodland will sequester the most carbon and open pasture the least. The author suggested that changes in government policy and farm subsidies could be the most cost-effective way to encourage silvopasture as an agricultural land use in Wales.

The results of the above experiments have shown that silvopastoral systems have a higher C sequestration potential than pure pasture, but the C stocks in silvopastoral systems were less than pure woodlands. This is expected because as planting density increases aboveground biomass increases, and consequently the amount of C sequestered increases. Tree stands that have denser canopy cover continuously add organic matter to the soil resulting in higher soil organic matter content (Patenaude *et al.*, 2003). The fact that the amount of carbon sequestered in the soil decreased with depth is also an expected result of the downward movement of organic matter by leaching and eluviations. The results of the above experiments have also shown that soil organic carbon (SOC) was a major component of ecosystem carbon stocks. The findings of the above studies of 245 t C ha^{-1} for the woodland control plots at Henfaes is comparable to the value of 228 t C ha^{-1} reported by Broadmeadow and Matthews (2003) for woodlands in Wales. Thus, based on the above estimates made at Henfaes SSEF, it may be concluded that silvopastoral systems with higher density of trees (400 stems ha^{-1}) have a potential to sequester more C than open pasture and lower density silvopastoral systems (100 stems ha^{-1}).

Soil improvement and maintenance

One of the environmental benefits of incorporating trees onto pasture is soil amelioration by the trees. Trees are known to improve the productivity of the soil beneath them. Research results have shown that the main tree-mediated processes that determine the extent and rate of soil improvement by trees include increased nitrogen (N) input by N_2-fixing trees, enhanced availability of nutrients resulting from production and decomposition of tree biomass, and greater uptake and utilization of nutrients from deeper layers of soils by deep-rooted trees (Young, 1997).

The role of N_2-fixing trees in improving soil fertility in silvopastoral systems was investigated at Henfaes SSEF by Martin (1995), Teklehaimanot and Martin (1998), Mmolotsi (2004), Teklehaimanot and Mmolotsi (2007), and Mmolotsi and Teklehaimanot (2008).

Martin (1995) and Teklehaimanot and Martin (1998) assessed the nitrogen fixing capability of red alder (*Alnus rubra*) in silvopastoral systems at Henfaes SSEF by comparing it with the pasture component, white clover (*Trifolium repens*). The diurnal and seasonal patterns of nitrogenase activity of red alder and white clover was assessed using the acetylene reduction assay. No obvious diurnal patterns of nitrogenase activity were found in either red alder or white clover in summer and no significant variations in nitrogenase activity were observed between day and night. However, in autumn, pronounced diurnal patterns were observed in both species. Significantly higher rates of nitrogenase activity per unit dry weigh (dwt) of nodules were detected at 1500 hours in red alder, whereas, in white clover, significantly higher rates were obtained at 2100 hours. Seasonal rates of nitrogenase activity showed significantly higher activity in summer, which subsequently decreased in autumn, to reach very low levels in the winter.

The rates of nitrogenase activity of white clover were consistently higher than those of red alder both diurnally and seasonally. In the three seasons sampled, the average nitrogenase activity for white clover was 66.42 µmol C_2H_4 g nodule dwt^{-1} h^{-1}, which was 3.5 times higher than the 18.67 µmol C_2H_4 g nodule dwt^{-1} h^{-1} obtained for red alder. The low nitrogenase activity in red alder may be due to the young age of the trees. They were only three years old at the time of the investigation. Yet, the trees were actively fixing N and thus the results show that the trees were playing their soil amelioration potential role in silvopastoral systems as early as at three years of age.

Mmolotsi (2004) and Teklehaimanot and Mmolotsi (2007) also studied the nitrogen fixing capability of red alder at the age of 11 years in silvopastoral systems at Henfaes SSEF using nitrogen-15 natural abundance method. Results showed that depleted $\delta^{15}N$ values close to zero were recorded in red alder plant parts except in root nodules and the soil, indicating that a large proportion of nitrogen in red alder was fixed from the atmosphere. The depleted $\delta^{15}N$ values indicate a signature of ^{15}N that was similar to that of the N in the atmosphere, showing that the atmosphere was the main N source in red alder. This also indicates that the red alder was efficiently fixing atmospheric N as shown by the high fraction of N derived from the atmosphere (FNdfa) (average 85%).

The results of the study showed that $\delta^{15}N$ varied between seasons. $\delta^{15}N$ values for the summer and autumn seasons were negative for red alder indicating active N fixation during these periods. The FNdfa values were 90 and 99% for summer and autumn, respectively. The average values of $\delta^{15}N$ for the winter and spring seasons were positive but close to zero in the red alder that indicate reduced N fixation during these periods. FNdfa values were 85 and 64% for winter and spring, respectively.

Nitrogen fixation estimates by the acetylene reduction assay method also showed that the mean nitrogenase activity in red alder nodules was high in summer and autumn when temperature and moisture regimes were favourable, and N fixing activity was significantly reduced in the winter periods, probably due to low temperature (Teklehaimanot and Martin 1998; Tripp et al. 1979). Similar results were obtained by Binkley et al. (1985) in red alder.

The root nodules of the red alder and the soil of the site showed enriched values of ^{15}N. The positive $\delta^{15}N$ values in root nodules show that root nodules were enriched with ^{15}N indicating that the soil was the source of nitrogen for root nodules of red alder. The results of the present study are consistent with those reported by Tjepkema *et al*. (2000) who reported that the nodules of *Alnus glutinosa* were consistently enriched in ^{15}N relative to other plant parts. The enriched $\delta^{15}N$ values (5.95‰) of soil were also consistent with those reported between 5.0 and 5.8‰ in forest soils by Kreibich and Kern (2000).

Overall, planting density had significant effect on the rate of N fixation in red alder. It was estimated that 65.55 and 334.14 kg N ha^{-1} was fixed by red alder in the silvopastoral treatment plots and woodland controls, respectively (Teklehaimanot and Mmolotsi, 2007). This included N fixed in leaves, wood, and roots. By considering only leaves, as done in most of the studies on N fixation (Coté and Camire, 1984), the amount of N derived from the atmosphere in leaves was 9.22 and 57.63 kg N ha^{-1} in silvopasture and woodland control, respectively. The woodland control value agrees with that (53 kg N ha^{-1} in both mixed and pure stands of alder grown in Canada) reported by Coté and Camire (1984).

A study was carried out by Mmolotsi and Teklehaimanot (2008) to estimate the contribution of red alder to soil organic matter and nitrogen content in a silvopastoral system at Henfaes SSEF. They quantified fine roots and roots nodules over the four seasons in silvopastoral and woodland control plots of red alder by collecting soil samples in each season at three sampling points (0.30 m, 0.50 m and 1.00 m distance from the base of each tree) from nine trees. Results showed that there were significant differences in the density of live fine root between seasons and treatments ($p < 0.001$). The mean weight density of live fine root over the four seasons in silvopastoral and woodland control was 0.27±0.01 $kg \cdot m^{-3}$ and 0.54±0.03 $kg \cdot m^{-3}$, respectively. Weight density of dead root in each treatment plot remained constant throughout the year. The mean weight density of dead root was also significantly different ($p < 0.01$) between woodland control and silvopastoral treatments. Weight density of live and dead root nodule was both constant throughout the year and between the different sampling distances. Live and dead fine root densities of red alder were 2700 and 5400 kg ha^{-1} and 360 and 790 kg ha^{-1} in silvopastoral plots and woodland controls, respectively.

The mean weight densities of live and dead root nodule over the four seasons were 0.09±0.03 $kg \cdot m^{-3}$ and 0.05±0.03 $kg \cdot m^{-3}$ in silvopastoral and 0.08±0.02 $kg \cdot m^{-3}$ and 0.03±0.01 $kg \cdot m^{-3}$ in the woodland control plots, respectively. Live and dead root nodule weight densities of red alder yielded 880 and 520 kg ha^{-1} in silvopastoral plots, and 800 and 310 kg ha^{-1} in woodland controls, respectively. According to the results of the present study, the amount of organic matter potentially added to the soil due to senescent leaves and dead roots and root nodules was estimated at 4.0 and 9.1 t ha^{-1} yr^{-1}, in silvopastoral plots and woodland controls, respectively. These results showed that red alder has a potential to improve and maintain soil fertility in silvopasture.

The study showed that significantly large quantities of dead fine roots and root nodules were found in soils within the silvopasture and woodland control treatments. These contribute significantly to soil organic matter and nitrogen content of the soil (Mmolotsi and Teklehaimanot, 2008). Consequently, the results of the above studies show that by planting N_2 fixing trees in silvopastoral systems, N is provided, and the level of nutrients in the soil is increased.

The high soil organic matter content at Henfaes SSEF has important and diverse implications for soil quality. Accumulation of more soil organic matter in the soil of silvopastoral systems than in open pasture improves and maintains soil physical, chemical and biological properties by reducing bulk density and increasing water-holding capacity and nutrient availability. Soil organic matter is a key attribute of soil quality vital to many of the soil functions (e.g. erosion control, nutrient cycling, and water infiltration and quality) (Young, 1997). Therefore, the high soil organic matter in silvopastoral systems as observed at Henfaes SSEF indicates a high ecosystem service function of Silvopastoral systems in terms of soil quality improvement and maintenance.

Water management

The amount of water present in a system is a useful measure of plant and soil water status. Climate, soil and vegetation influence water relations of forests (Whitehead, 1984) and agroforestry systems. Water balance has a great influence on tree growth and survival as tree growth depends on water availability. On the other hand, trees are also considered as important factors in the water balance in terms of their influence on interception, transpiration, and, hence, runoff and drainage (Landsberg and Gower, 1997).

Introducing trees on pasture or re-spacing of existing tree stands to create silvopastoral systems can change the water balance of the site. This can have direct effects on the productivity of trees and livestock at the site or on water resource management of a catchment or region.

An experiment was undertaken to study the effect of widely spaced trees on the water balance of a silvopastoral system in Glentress forest, Scotland by Teklehaimanot *et al*. (1991a). The trees were re-spaced at intervals of 4, 6 and 8 m by thinning the Sitka spruce trees originally planted at 2 m spacing to create a silvopastoral system and study the effects of widely spaced trees on the microclimate and consequently on herbage production from sown grass swords (Sibbald *et al*., 1991).

Teklehaimanot *et al*. (1991a) measured rainfall interception loss, which is an important component of the water balance of the system, at Glentress forest silvopastoral systems experimental site. Measurement of rainfall interception loss is an essential prerequisite for a quantitative prediction of the effects of widely spaced trees in silvopastoral system on the water management of a site. They measured throughfall, stemflow and interception loss using the traditional volume balance method in three widely spaced treatment plots of 4, 6 and 8 m and a forestry control plot of 2 m spacing.

The results showed that, on average, rainfall interception loss as a percentage of gross rainfall was 33, 24, 15 and 9% in the 2, 4, 6 and 8 m spacing treatments, respectively. The results also showed that rainfall interception loss was not directly proportional to the density of trees but it was related to the number of trees per hectare by a rectangular hyperbolic function.

The difference in interception loss between spacing treatments was, therefore, attributed to the difference in boundary layer conductance. Boundary layer conductance per tree increased with spacing from 0.82 mm s^{-1} in the 2-m spacing forestry control treatment to 5.92 mm s^{-1} in the widely spaced 8 m treatment (Teklehaimanot *et al*., 1991a). The high boundary layer conductance per tree in the 8-m spacing was caused by a high rate of evaporation per tree due to increased ventilation and air turbulence in widely spaced stands.

The effects of trees on the components of water balance of silvopastoral systems was also investigated at Henfaes SSEF by Rakkibu (1998), Temba (1999), Kuflu (2000), and Kondziela, (2011). With the exception of Kondziela (2011), all the others found significant effects of tree density and tree species on some of the components of the water balance of Henfaes SSEF and these are described in detail below.

Rakkibu (1998) assessed the effect of tree density on tree transpiration by measuring sapflow in red alder trees using Thermal Dissipation Probe. Planting density was found to modify individual tree sapflow. Mean sapflow per tree was found to be lower at woodland control being 0.29 dm^3h^{-1} compared with 0.44 dm^3 h^{-1} at 400 stems ha^{-1} silvopastoral treatment and the difference was highly significant ($p< 0.001$). The higher sapflow in widely spaced silvopastoral plot was related to a high rate of crown transpiration caused by greater canopy exposure to wind and sunlight. Sapflow was found positively correlated with solar radiation and air temperature and negatively correlated with relative humidity. Rakkibu (1998) also found high significant difference ($p<0.001$) in sapflow between the three treatment blocks of red alder at the site. This could be attributed to the difference in water table between the three blocks. Water table was found to be very shallow in block 1 (1 m) and fairly deep in block 3. Trees in block 1 are more likely to transpire more water because of their greater proximity to soil water than in block 3. Similar results were obtained by Lu *et al*. (1995) who observed significant differences in transpiration between dry and wet plots. Again, due to abundance of soil water, trees in block 1 and block 2 grew faster than trees in block 3 as alder is known to prefer wet sites. Thus, trees in block 1 transpired significantly more water than those in block 3 due to their larger diameter and bigger crown area. The greater mean sapflow in alder silvopastoral plots than in alder woodland control plot was probably because trees at wide spacing are more exposed to sunlight and wind than trees in closely spaced trees. Similar results were also reported by Morikawa *et al*. (1986) who observed that the rate of sapflow per tree was higher in a thinned plot at a given level of solar radiation, and that the difference between sapflow before and after thinning increased with solar radiation in *Chamaecyparis obtusa* stands. Lower sapflow per tree in alder woodland control may be due to mutual shading of trees as reported by Granier *et al*. (1996). Similar relationship of sapflow with tree densities have been shown by Eastham *et al.* (1990) who reported that trees planted at lower densities were able to maintain higher sapflow rates per tree than trees at higher densities despite higher evaporation from pasture in low densities. This indicates that trees may successfully compete with pasture for soil water, possibly because rooting patterns lead to withdrawal of water predominantly from different soil horizons (Eastham *et al*., 1990).

Temba (1999) measured soil moisture content in 400 stems ha^{-1} silvopastoral plots and 2500 stems ha^{-1} woodland control plots of both red alder and sycamore as well as in the pasture control plots without trees at Henfaes SSEF. Measurements in plots with trees were made at 0.5 meter and 2.5-meter distance from the tree base, and in four directions (North, South, West and East). Soil moisture was found to be consistently higher in the pasture control (0.35 m^3m^{-3}) compared to silvopastoral and woodland control plots. Also, soil moisture was found to be higher in silvopastoral than in woodland control plots. Soil moisture at 0.5 m distance from tree base was found to be higher in sycamore (0.28 m^3m^{-3}) compared to red alder (0.22 m^3m^{-3}). At 2.5 m distance, however, soil moisture was found to be similar to that of pasture control plots but significantly higher ($p<0.001$) than at 0.5 m distance. The significant variation in soil moisture as distance increased from the tree, that is, the increase in soil moisture with increasing distance from the tree trunk, can be explained in various ways. The lower soil moisture at the base of tree canopy may be due to more soil compaction at 0.5 m compared to 2.5 m distance from the tree trunk as a result of trampling by sheep that tend to concentrate around trees for shade (Penn *et al*. 1994; Sibbald *et al*., 1995; Sibbald *et al*., 2001;

Bezkorowajnyj *et al*., 1993). Compaction impedes infiltration which results in low soil moisture content. Penn *et al*. (1994) found that the soil at a depth of 10 cm on the agroforestry plot was drier closer (0.5 m) to tree throughout the year compared to the soil at 2.5 m away from the trunk.

Kuflu (2000) investigated the effect of tree density and species on throughfall and soil moisture content at Henfaes SSEF. Results showed that throughfall was higher under sycamore (93 and 89% of gross rainfall) than under alder (74 and 49%) at silvopastoral and woodland control plots, respectively. The author attributed this difference to the smaller canopy cover and shorter height of sycamore. The 49% throughfall value of alder in the woodland control plot is in close agreement with the 50% reported by Teklehaimanot *et al.* (1991a) for 19-year-old Sitka spruce plantation with a density of 2500 trees ha^{-1}. There was more throughfall in silvopastoral plots than in woodland control plots at Henfaes SSEF because the lower tree density in the silvopastoral plots (400 stems ha^{-1}) intercepted less rainfall than the higher tree density in woodland control plots (2500 stems ha^{-1}). Teklehaimanot *et al*. (1991a), also observed that there was more throughfall at wider spacing. The higher throughfall in sycamore than in alder may be attributed to the variation between the species (sycamore and alder) in the height and diameter and shape of trees as they grow, and on the degree of canopy cover. Soil moisture was also observed by Kuflu (2000) to be higher in silvopastoral plots (0.304 and 0.273 m^3m^{-3}) than in woodland control plots (0.265 and 0.189 m^3m^{-3}) under sycamore and alder, respectively, but there were no significant differences in soil moisture content between the sycamore silvopastoral plots and the pasture control plots (0.293 m^3m^{-3}). The author attributed this result to the lower tree density in the silvopastoral treatments and the absence of trees in pure pasture.

Based on the results of the above studies, it may be concluded that silvopastoral systems are better than pure woodlands in improving and maintaining the water balance of the soil by modifying one or two of its components.

Biodiversity enhancement

Silvopastoral system enhances biodiversity due to the diverse environmental conditions that are created within (vegetation structure, shading and moisture). It increases connectivity within landscape components which benefit the mobility of animals thus reducing habitat fragmentation (Rois-Díaz *et al*., 2006).

Various authors have examined how silvopastoral systems enhance biodiversity (e.g. McEvoy 2005; Burgess, 1999; McAdam *et al*. 1999b, 2007a; Agnew and Sibbald 1996; Wang, 1999; Cuthbertson and McAdam, 1996; Toal and McAdam 1995; Crowe and McAdam, 1993).

Burgess, (1999) notes that experience in a number of trials across the UK has shown that biodiversity increases as a result of silvopastoral agroforestry. In his review of the potential impact of agroforestry systems on the diversity of plants and animals on British farms, he suggests that the introduction of silvopastoral systems can lead to an increase in the diversity of invertebrates and perhaps birds on grassland farms.

The impact of silvopastoral systems on aspects of biodiversity (carabid beetles, spiders, birds and flora) was investigated when trees had been established for up to 8 years at the North Ireland's UK National Network Experiment. McAdam *et al.* (1999b) found greater biodiversity levels in silvopastoral systems than in both open grassland and pure woodland systems. More spiders were collected from silvopasture than either pasture or woodland treatments. Carabid beetles were more numerous and from a wider range of species in the silvopasture than open pasture (Cuthbertson and McAdam 1996; Whiteside *et al*. 1998). Numbers of juvenile earthworms were higher in silvopasture than grassland (Whiteside *et al*., 1998). Plant diversity was also greater (but not significantly so) near trees than in open pasture (McAdam 1996;

McAdam and Hoppé 1996). Toal and McAdam (1995**)** found that, generally, significantly more birds were recorded on silvopasture in summer and winter than either open pasture or woodland. Similar findings were reported by Bergmeier *et al* (2010), in their survey of wood-pasture habitats in Europe, that silvopastures are a "habitat of importance" for at least 37 European bird species, while for another 18 species, a high proportion of their European populations uses this habitat too.

McAdam *et al*. (2007a) also reported the results of the studies carried out on the effect of silvopastoral systems on biodiversity in all the sites of the UK's SNNE. The results showed that silvopastoral systems attracted invertebrates of epigeal groups which may have provided an enhanced food supply which attracted birds. It was concluded that, even at this early stage, silvopastoral systems have an impact on birds: birds normally associated with woodland are being attracted to silvopasture along with birds normally found in open fields.

Heron (1999) assessed ground fauna six years after the establishment of the silvopastoral experiment at Henfaes. All the silvopastoral treatments had bigger populations of ground beetle and woodlice than the woodland control treatments and were found in higher numbers near the tree bases. Centipedes/millipedes found to occur mainly in the woodland control plots decreased as tree density decreased. Springtails were found to occur less in the silvopastoral treatments than in the woodland control treatments suggesting that a competitive interaction between ground beetles and springtails may exist. Based on these findings the author concluded that silvopasture treatments had greater habitat diversity.

Overall, the results of the above studies show that, even at an early stage, silvopastoral systems can significantly enhance biodiversity, confirming a general trend noticed across Europe by Benton *et al*. (2003) that structural heterogeneity created by agroforestry can increase biodiversity in previously intensively farmed grassland. Although the plot size in the above experiments (overall mean 0.56 ha), spatial arrangement of the plot and influence of adjacent habitats cast concern on the actual quantifiable value of the results, for comparative purposes they indicate trends which will have important long-term wildlife habitat implications. The creation of land-use mosaics involving both silvopasture and open grassland will offer further opportunity for landscape heterogeneity which will benefit birds and other fauna.

Highlights of benefits and contributions to knowledge base

A few highlights of contributions of the reviewed research papers to knowledge base include:

- There are negligible effects of the trees on pasture within the first ten years of establishing the Henfaes SSEF, irrespective of the tree species,
- High quality timber and firewood can be produced from silvopastoral systems.
- Trees planted in clumps presented better form and growth than the widely spaced trees.
- The poor performance of the wider spaced trees was attributed to exposure to wind and to the effects of animals through browsing or soil compaction.
- Trees in agroforestry systems sequestered more carbon per unit area compared to a monoculture field of crop plants or pure pasture.
- There was no reduction in animal production ten years after planting despite interception of up to 10% of total photosynthetically active radiation by the developing tree canopy.
- Soil and water quality improvement and maintenance is more efficient in silvopastoral systems compared to pure woodlands.
- Greater biodiversity levels were found in silvopastoral systems than in both open grassland and pure woodland systems.

- Silvopastoral agroforestry system is a more viable economic undertaking compared to conventional livestock grazing and pure forestry systems.

GAPS AND AREAS FOR FUTURE RESEARCH

The foregoing review and discussion of the ecosystem service topics clearly suggest that the UK's SNNE, though at its infancy, is contributing considerably to the biophysical and economic understanding of tree-pasture-livestock interactions. Substantial and impressive research studies have been conducted at the experiment so far, but the link between scientific knowledge and effective field application for the benefit of the sheep farmers and woodland owners is still lacking. However, some areas remained either under-studied or completely neglected. The following research gaps and areas deserve attention:

a) There is the need to conduct a more exhaustive, holistic and updated review of research papers and articles written on the UK's SNNE to include more information from other institutions and experimental sites.
b) As management interventions and invasion of pasture by unwanted weeds may have taken place over the years, there is the need to study the pattern of temporal and spatial changes in the understory pasture species composition and abundance in silvopasture.
c) Applying biomass allometric equations developed for trees grown in pure forestry systems to trees on agroforestry scale analysis can be challenging because of the disparity in their growth forms. This underscores the imperative need for the development of species specific allometric equations for trees grown in agroforestry systems to evade this constraint.
d) Forage production and nutrient content are known to determine the productivity of the grazing animal, and thus the productivity of the grazing system. Since there is a strong relationship between understory forage production and canopy closure/light intensity, there is the need to evaluate forages grown in silvopastoral practices for the effect of canopy/light on forage production and nutrient quality.
e) While the environmental benefits from agroforestry systems are relatively well understood, considerable uncertainty remains about the potential economic profitability of silvopastoral systems compared to monoculture, and given the current difficulty in securing incentives to engage in agroforestry, there is the need to explore the financial and economic viability of silvopastoral system vis-à-vis non-agroforestry farm management systems.

CONCLUSION

Using the ecosystem service framework, this study systematically reviewed and synthesised all the scientific literature that has so far been conducted on the ecosystem services of the UK's SNNE, the Henfaes Silvopastoral Systems Experimental Farm (SSEF) of Bangor University, Wales, and other studies in temperate Europe from 1988 to 2012. It summarized and identified what has been done so far, the benefits and contributions to our knowledge base, and potential knowledge gaps and priorities for future research from the data of ecosystem services in silvopastoral agroforestry systems.

The number of annual studies on ecosystem services of the UK's Silvopastoral National Network Experiment and temperate Europe were greatest in the mid and late 1990s than in any other time over the 20-year study period. Again, results of the systematic review show that 66 research studies were conducted over the 20-year study period on ecosystem services of the UK's SNNE and temperate Europe, of which forty-five percent were produced based on studies at Henfaes SSEF, thirty-two percent at UK's SNNE, twelve percent were from other

silvopastoral systems trials in the UK, and eleven percent were from European-wide silvopastoral systems studies.
Furthermore, the ecosystem service assessment of the studied silvopasture generally focused on provisioning, regulating, and supporting services to the exclusion of cultural services. Similarly, greater attention was given to biophysical assessment approaches and quantifiable indicators than to monetary approaches and indicators. The study also highlighted some of the contributions of the reviewed research papers to knowledge base as well as research gaps and areas that deserve attention.

STUDY LIMITATIONS

The result reveals a considerable number of studies on silvopasture and ecosystem services in the United Kingdom and some parts of Europe as well as a clear picture of the data structure, even though this body of literature (n=66) is not large when compared to the vast extent of silvopasture sites in the United Kingdom and temperate Europe. Majority of the reviewed research initiatives were the Henfaes SSEF of Bangor University and the UK's SNNE (Table 1), whereas silvopasture systems in other parts of the UK and Europe were given less attention. This limitation on the number of studies is an indication that little research had been done on the topic of ecosystem services in silvopasture systems up to the point, and that this branch of research is only in its infancy.

The review also shows how ecosystem service assessment of the studied silvopasture generally focused on provisioning, regulating, and supporting services, such as timber or fuelwood potential, pasture/livestock management, carbon sequestration, water management, soil improvement, and biodiversity enhancement, while no attention whatsoever was given to cultural services. Likewise, there was a strong dominance of biophysical assessment approaches and quantifiable indicators, and less attention to monetary approaches and indicators.

Care should be taken when interpreting the results and conclusions of this study. It is most likely that not all relevant scientific literature addressing the research questions of the ecosystem services under review were captured. The search terms might have missed vital information in relevant publications and grey literatures, such as reports from governments and other institutions or literature published in magazines/journals. Moreover, information from other institutions and experimental sites in the United Kingdom could not be represented because of time and financial constraints. Therefore, there is a clear need to conduct a more exhaustive, holistic and updated review of research papers and articles written on the UK's SNNE silvopasture to include more information from other institutions and experimental sites. For more comprehensive understanding of UK and other European Silvopasture, empirical research should be directed to a wider variety of research approaches and to a wider coverage of ecosystem services to include studies of cultural ecosystem services, as well as studies of the financial and economic implications of silvopasture and the direct contributions of agroforestry to human well-being (e.g. in terms of public health benefits),

ACKNOWLEDGEMENTS

The completion of this research study was made possible with the assistance, encouragement and guidance of the following people and organisations to whom I owe my sincerest gratitude:

Foremost, I owe my deepest gratitude to my supervisors, Dr. James Walmsley and Dr. Mark Rayment, for their sustained guidance, wisdom, thoroughness, support, patience and commitment over the many years of my field research and during the writing up process despite their many other academic commitments. Both supervisors were instrumental in the development of concepts and understanding of silvopastoral agroforestry systems that enabled this study.

I am deeply indebted to the Nigerian Tertiary Education Trust Fund (TETFUND) for sponsoring my PhD research programme in agroforestry under its Academic Staff Training and Development Programme as well as to the Management of Chukwuemeka Odumegwu Ojukwu University (COOU) (Former Anambra State University), Anambra State, Nigeria for granting me the leave to undertake this research programme.

I am also very grateful to other staff and fellow students of the School of Environment, Natural Resources and Geography (SENRGY) at Bangor University who played significant roles during my studies. My special thanks will go to Ian Harris, Mrs. Llinos Hughes, Mark Hughes, and all other staff at the Bangor University research farm at Henfaes (the site of the Silvopastoral National Network Experiment) for providing me with useful information on the management of the research farm and for their support, assistance and patience during my data collection process and laboratory works.

My greatest thanks go to the Farm Woodland Forum for awarding me the Lynton Incoll Memorial Scholarship that enabled me to present some of my PhD research chapters at the 2014 Farm Woodland Forum annual meeting in Devon, UK. I am equally grateful to all the researchers, staff, students and volunteers who have contributed to the huge body of knowledge that has been generated by the various UK's Silvopastoral National Network Experiments.

Last but certainly not least, the encouragement I received from my friends and family was phenomenal, particularly my spouse and children, for their love, support, understanding, and extreme patience over the period of my research programme.

Finally, I give gratitude to God for giving me enough spirit and strength to surmount the various obstacles encountered in making the completion of my research studies a reality.

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Journal of Agricultural Policy
ISSN 2520-7548 (Online)
Vol.3, Issue No.1, Pp 75- , 2020 www.carijournals.org

Appendix 1: List of references in relation to ecosystem service functions addressed.

S/N	Authors / References	Provisioning services		Regulating services	Supporting services		
		Timber or fuel potential	Tree/Pasture/ Livestock interaction	Carbon sequestration	Soil improvement	Water management	Biodiversity enhancement
1	Agard (2011)			x			
2	Agnew and Sibbald (1996)						x
3	Benjamin (2010)			x			
4	Bergmeier et al (2010)						x
5	Bezkorowajnyi *et al*. (1993)	x				x	
6	Broadmeadow and Matthews			x			
7	Burgess, P.J. (1999)						x
8	Crowe and McAdam (1993)						x
9	Cuthbertson and McAdam (1996)						x
10	Eastham *et al*. (1990)					x	
11	Englund (1995)	x					
12	Follain *et al*. (2007)			x			
13	Gerety (1998)	x					
14	Granier *et al*. (1996)					x	
15	Green *et al*. (1995)	x					
16	Heron (1999)						x
17	Hislop and Claridge (2000)		x				
18	Howe (1997)	x					
19	Islam (2000)	x					
20	Jariu (2000)		x				
21	Kasahun *et al*. (2011			x			
22	Khanal (2011)			x			

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23	Kondziela (2011)					x	
24	Kreibich and Kern (2000)				x		
25	Kuflu (2000)					x	
26	Lu *et al.* (1995)					x	
27	Martin (1995)				x		
28	McAdam (1996)						x
29	McAdam and Hoppé (1996)						x
30	McAdam *et al.* (1999a, 1999b)		x				x
31	McAdam *et al.* (2007a						x
32	McArthur (1991)		x				
33	Mmolotsi (2004)				x		x
34	Mmolotsi and Teklehaimanot	x					
35	Mmolotsi and Teklehaimanot				x		
36	Ng'atigwa (1997)	x	x				
37	Nghitoolwa (2001)		x				
38	Onyeka (1998)		x				
39	Patenaude *et al.* (2003)			x			
40	Penn *et al.* (1994)				x	x	
41	Rakkibu (1998)					x	
42	Ramdial (2010)			x			
43	Roberts (1995)	x					
44	Rodwell (2009)			x			
45	Rois-Díaz et al. (2006)						x
46	Sibbald and Dalziel (2000)		x				
47	Sibbald and Sinclair, 1990)						
48	Sibbald *et al.* (1991)		x				
49	Sibbald *et al.* (1995)		x				
50	Sibbald *et al.* (2001)	x	x				
51	Teklehaimanot and Martin (1999)				x		
52	Teklehaimanot and Mmolotsi				x		

53	Teklehaimanot *et al*., (1991a)					x	
54	Teklehaimanot *et al*., (2002)	x	x				
55	Temba (1999)					x	
56	Toal and McAdam (1995)						x
57	Wang (1999)				x		
58	Winslade (1996)	x					
59	Zapater (1998	x	x				
		13	**13**	**9**	**8**	**10**	**13**