Agricultural sustainability of the silk industry

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Sericulture, which is the production of silk fibre or reeled silk thread from silkworm cocoons, is an ancient industry. It has been carried out in Japan since 600 C.E., if not earlier (Shimatsu, 2004), and there is evidence for the production of silk fibre, thread, and fabric in China and India as far back as 2500 B.C.E (Good, Kenoyer, & Meadow, 2009). It is regarded as a relatively high impact industry compared to other fibre production industries such as wool and cotton (Astudillo, Thalwitz, & Vollrath, 2014), but there is historical evidence that it need not be a polluting or unsustainable industry. Information and technologies exist to mitigate the environmental impacts of sericulture, and as the product is relatively high value and in demand it has the potential to help alleviate poverty in some regions. Historical trends indicate that this industry has the capacity for longevity, and has the inherent resiliency to be able to adapt to new pressures.

Silk production is a relatively simple. The process of producing silk thread has two basic inputs: silkworm cocoons and labour. The outputs are reeled silk thread or silk fibre for spinning, and unreelable silk fibre which may be spun, used in the production of polymer composites (Ho, Wang, & Lau, 2012), or may be regarded as a waste product. Reeled silk filament may then be ‘thrown’ to create a twisted silk thread (Jones, 1987). The production of the cocoons needed to produce silk thread requires mulberry leaves as silkworm fodder, and produces, along with the cocoons, litter from the silkworm rearing trays, and dead pupae. The mulberry culture itself also has associated waste streams, similar to other silvicultural production systems (Astudillo et al., 2014).

Aside from the rearing of the silkworms and the mulberry plants for their food, there are few additional steps in processing the silk. Cocoons are put through a degumming process to prepare them (Arimoto, Nakajima, & Okazaki, 2014), and are then unwound and the silk filament reeled onto bobbins either by hand or by machine to form raw silk thread (Shimatsu, 2004). Degumming is the process of removing the sticky sericin protein which naturally covers the fibroin core of the silk filament (Ho et al., 2012). The sericin is usually dissolved using hot water, although other agents may be used such as alkaline solutions, soap or detergents, or organic acids (Ho et al., 2012). As such, the processing of the cocoons requires water, and energy to heat the water, as well as potentially soap, alkali, or mild acids. The waste from this part of the process is the dissolved sericin protein in the water, which can be composted, and the used alkali, soap or acid if it is used. In short, most of the waste streams from silk production are not significantly polluting.

Modern silk production is highly industrialised. The production of the cocoons is done on farm under intensive management, usually using mulberry leaves grown on farm as fodder (Astudillo et al., 2014), although there is no inherent requirement for the mulberries to be grown on the same farm as the silkworms. Reeling is done by machine in order to produce high quality silk thread which is acceptable to international markets (Astudillo et al., 2014). While artisanal and cottage production of silk, including hand reeling, is still possible it is not widely practiced. It is debatable if small scale silk end to end silk production could be commercially viable in the modern market.

The industrialisation of silk production, moving from an artisan cottage industry to large scale, factory-based production occurred across the 18th and 19th Centuries C.E. The British silk industry was the world's first modern factory industry (Jones, 1987). A five story silk mill was built in Derby in 1718, using water power to drive machinery for winding reeled silk fibre into twisted silk thread (Jones, 1987). Similar machinery was already in use in Italy at that time (Jones, 1987). In 19th Century Japan, vertically integrated silk production was carried out in many mountain communities, with each household or smallholding carrying out the full array of tasks from rearing and breeding silkworms to degumming and reeling the silk thread (Shimatsu, 2004). Increasing Western influences over the 19th Century led to the use of factories for silk reeling and a significant decrease in vertically integrated silk production (Shimatsu, 2004). However, in neither British nor Japanese silk production did the increased industrialisation of the silk reeling and throwing of silk thread have any great effect on the production of silkworm cocoons on farm (Jones, 1987; Shimatsu, 2004).

These early technologies, in the form of factories and machinery, did not significantly improve the efficiency of the production of fine silk thread. The machines used for reeling silk and throwing silk thread may have improved the speed of silk production in 18th Century Britain, but the quality of the silk was not high (Jones, 1987). In Japan, production actually decreased when factory production was introduced (Shimatsu, 2004). While modern machinery for silk reeling does provide a benefit in terms of the amount of labour required and thus the speed with which cocoons can be processed, it is the advances in silkworm and mulberry breeding which have provided the most benefit. These breeding efforts have created new strains of both mulberry and silkworm which are suited to climatic conditions in different regions, increasing production in areas where neither silkworms nor mulberries thrive naturally (Ambrus, 1996; Doss et al., 2011a). This has allowed the production of large quantities of raw silk in India and South America, rather than confining it to east Asia and some regions of Europe as it was in the 18th and 19th Centuries.

The production of raw silk is mainly carried out in poorer regions, as it has been since the 18th Century. Although silk is a prestigious product, it is labour intensive to produce the cocoons. Silkworm cultivation requires the silkworms to be monitored and attended to at least three times a day, every day, with no off-season (Ambrus, 1996). It requires as many as eleven labourers per kilogram of silk produced (Prakasam & Ravi, 2014). This can be viewed as both a positive and negative factor, depending on the cost of labour. When labour costs are low, as in many developing nations, then consistent employment for multiple people is a benefit. This is especially true for a relatively profitable product such as silk. However, as labour costs rise, it is less desirable to require large labour inputs to production as the costs decrease profitability.

Any agricultural enterprise has the potential to be or become sustainable. Sustainable agriculture, after all, may be broadly defined as any form of agricultural production which does not destroy the systems on which it relies and may thus continue to exist indefinitely (Hansen, 1996). The definition of what the systems are on which any given agricultural industry relies is more difficult, as they may range from the purely practical concerns of soil fertility and health to the more sociologically constructed issues of traditional agricultural techniques, communities, and equity (Hansen, 1996). However, once these supporting systems have been identified and defined for a specific industry and context, modifying the practices of that industry to avoid damaging or destroying them is eminently possible.

For the purposes of assessing the sustainability of the global silk industry, it is important to clarify which systems are relevant and must be maintained in order to call the industry sustainable. The silk industry, like all agricultural industries, depends upon the ecological services provided by the natural environment, such as the recycling and provision of clean air and water. The systems that enable those ecological services are, therefore, one of the base support systems on which the silk industry depends. In the case of sericulture and the mulberry leaf crop which supports it, healthy, fertile soil is also important as the mulberries are grown directly in the ground. Silkworms thrive only in certain climatic conditions (Rahmathulla, 2012; Doss et al., 2011b), so climatic stability, without extreme fluctuations in humidity or temperature is also an important aspect of the ecological systems which support the silk industry. While any particular approach or strategy for maintaining or increasing agricultural production must be considered in its context, there are generalisations which can be made. one of these is that the environment forms one of the basic systems required for agricultural production, and specifically for the silk industry. Damaging or destroying those natural ecosystem processes will necessarily impact the capacity of the industry to continue.

The economic viability of the silk industry is also of significant impact to its sustainability (Prakasam & Ravi, 2014). This is the human side of sustainability, reflecting the fact that an industry which cannot contribute to the wellbeing of the people working in it will not be able to continue indefinitely. This incorporates both the basic capacity of the industry to generate a sufficient return to balance the costs of production, but also the social welfare associated with the industry. If profit accumulates but the benefits are not available to the people working in the industry, then it is as unsustainable over time as if the profit did not accumulate.

Silk production is, at present and using current methods and technologies, economically viable. Silk is a high value fibre (Astudillo et al., 2014) and there is clearly an ongoing market for it for use in luxury textiles (Ambrus, 1996). In addition to this, silk thread has been used for medical sutures for centuries (Ho et al., 2012), and continues to have many medical applications both new and existing. These include biomaterials such as gels and sponges, and reinforced polymer composites (Ho et al., 2012). There are also increasing numbers of industrial uses for silk fibre in various composite polymers due to its strength and flexibility. Demand exists and is unlikely to decrease in any significant way in the near future. The real question around the economic sustainability of the silk industry revolves around the costs involved in producing the silk fibre.

Silk reeling and sericulture have been a significant part of Japan’s economy since at least the early 20th Century (Arimoto et al., 2014), and contributed to its modernisation and industrialisation (Shimatsu, 2004). However, since the mid to late 20th Century both Japan and South Korea have been decreasing their silk production due to rising labour costs and land shortages, leaving countries such as China and Colombia to take on the primary production of raw silk fibre (Ambrus, 1996). Under the economic conditions of the mid-1990s that transition will have been of benefit to small farmers in developing nations, providing consistent employment on farm and a higher income per hectare than many other agricultural pursuits. That does not, however, indicate that the industry itself is economically sustainable; as wages rise and labour protection laws are put in place in developing nations, labour costs and therefore the costs of silk production will increase in those nations. For an industry to be called sustainable in economic terms, it must be capable of producing sufficient income to offset the costs of production even when labour protection laws exist and wages are high.

On the other hand, history indicates that silk production can be economically viable under the right circumstances. One of the factors leading to Japan's success in the silk industry in the 19th Century was the vertical integration of sericultural production in the country (Shimatsu, 2004). However, the loss of that vertical integration due to the introduction and import of Western technology and cultural practices led to a loss of efficiency and an increase in costs (Shimatsu, 2004). Vertical integration in 19th Century and early 20th Century Japanese mountain communities allowed the production of large quantities of high quality silk thread and silk fabric. It provided sufficient income to those communities that silk production was preferable to rice production for them, and their standard of living was relatively high (Shimatsu, 2004). All of this was possible without government aid or subsidies and without the use of modern industrial fertilisers and pesticides.

There is no reason to suppose that this is no longer the case, in spite of decreases in the price of silk in international trading markets. As an example, after Romania's entry into the European Union in 2007, the focus on increased productivity, diversification of production, and competitive efficiency made traditional sericultural methods no longer economically viable (Popescu, Matei, & Sladescu, 2008). Research at the University of Agricultural Sciences and Veterinary Medicine in Bucharest indicates that integrating multiple related enterprises, such as mulberry tree culture and silkworm breeding and supply may make the sericultural farms more economically viable than focusing only on silk production could do (Popescu et al., 2008). There may be economic benefits to increasing vertical integration in small farm silk production.

Aside from its economic viability using current production methods, there are a number of other factors affecting the sustainability of the silk industry. One of these is the method of handling the waste products of silk production, such as dead silkworm pupae and litter from the silkworm rearing containers. This waste is high in nitrogen and relatively valuable. As far back as 1989 the suggestion has been made that there may be uses for the silkworm litter, such as replacing chemical fertilisers for crop cultivation (Madan & Vasudevan, 1989), and the pupae are already used as poultry feed (Astudillo et al., 2014). Using the litter for mushroom cultivation has also been proposed (Madan & Vasudevan, 1989; Sharma & Madan, 1992), as has anaerobic digestion of the silkworm litter and dead pupae to produce biogas (Sharma & Madan, 1992; Vizwanath & Nand, 1994). In terms of environmental pollution and the production and utilisation of waste products, the silk industry could easily be made very sustainable. Taking up one or more of the above methods of handling the waste streams from silk production would be simple for farmers in both developing and developed nations.

In addition to the direct impacts of rearing silkworms, there are also indirect sustainability impacts. Mulberry (*Morus spp.*) leaves are the sole acceptable food source for *Bombyx mori* silkworms (Doss et al., 2011a). As a result, any consideration of the silk industry must also consider the impacts, both positive and negative, of mulberry agroforestry. There are many positive impacts and consequences of growing mulberry trees for the silk industry.

Mulberries are a hardy, broadly useful tree; the foliage can be fed to stock such as cattle, and the timber forms an acceptable fuel wood for fires (Prakasam & Ravi, 2014). They can be grown in mountainous and marginal areas (Shimatsu, 2004), and as with other perennial species planted in these areas they will protect against erosion by virtue of their root structure. Although a plantation of mulberries is not a natural woodland, and lacks the biodiversity associated with one, it does provide many of the same ecological services as any other stand of trees or shrubs. In addition to reducing erosion, water infiltration into the soil, nutrient recycling and soil fertility are improved (Kang, 1997) and soil carbon is increased (Howlett, Moreno, Mosquera Losada, Nair, & Nair, 2011). It is easy to see the benefits of growing mulberries, even outside their use as silkworm fodder.

However, many of the same traits which make mulberries a useful crop – their vigour, productivity, and ability to grow in marginal areas – can also lead to negative impacts. The most significant of these are fertiliser and pesticide runoff. While unfertilised trees and those which are lightly fertilised will produce large crops of mulberry leaves for use as silkworm fodder, fertilisation has been shown to significantly improve yields (Chen, Lu, Zhang, Wan, & Liu, 2009). Only around 30% - 50% of the fertiliser applied to crops is absorbed (Adler, 2002), and much of the rest ends up washed into local waterways. Similarly, a very small percentage of pesticides applied reach the target pest – in some cases as little as 1% (Adler, 2002) – and the remainder pollutes local water sources and soils.

There have been few studies to date considering the environmental impact of silk production. However, a 2014 full life cycle assessment of silk production in India found that the levels of fertiliser and pesticide run-off were substantial (Astudillo et al., 2014). Breeding of new mulberry varieties has focused on yield and production under high fertilisation rates, without due consideration of the impact of those fertilisation rates (Astudillo et al., 2014; Doss et al., 2011b). Pesticide applications and water usage are also high in order to maintain productivity and maximise yield. The average water requirement for a mulberry crop in India being in the region of 16 million litres per hectare per year (Astudillo et al., 2014). Of this, more than 50% is usually irrigation water as rainfall in the region is low. The combination of high fertiliser use and high water use indicates that the impact of fertiliser and pesticide runoff on waterways and groundwater is high.

Astudillo et al. (2014) also found that the rate of dry matter conversion from mulberry leaves to raw silk fibre was less than 5%. The waste products, including mulberry stems, leaves unsuitable for silkworms, and compostable waste from the silkworm rearing trays were used for fodder for other livestock, fuel, or composted (Astudillo et al., 2014). Pupae and sericin, which together make up more than 50% of the dry weight of the final output of the silkworm rearing phase of silk production, had no such uses associated with them (Astudillo et al., 2014) although they could also be composted or burned as fuel.

The other major area in which environmental impacts of the silk industry were found to be high were in emissions from wood burning for energy for the processing. In India, most of the reeling machinery and equipment used to kill the pupae by heating the cocoon are steam powered (Astudillo et al., 2014). Astudillo et al. (2014) estimated that 2.6 kg of fuel wood were used in the processing of 1 kg of fresh cocoon, producing less than 0.5 kg of silk filament. If one does not assume, as Astudillo et al. did, that the fuel wood is harvested sustainably then there is the additional impact of deforestation to consider. In either case, a significant amount of energy is used in the processing of silkworm cocoons.

Silk is a luxury textile, but it is also a product of some importance to medicine and to industrial manufacturing. However, if silk production is to remain a valuable, viable, and sustainable industry, some changes will need to be made. In India, the recommendations given by Prakasam and Ravi (2014) included the introduction of higher yielding mulberry varieties, the development of effective pest management measures, better marketing via production cooperatives or groups, and some market reforms such as quality-based pricing, and the reduction or elimination of duties. While this advice was intended for the Tamil Nadu region of India, it is relevant for other silk producing regions.

More specifically, the emissions and potential deforestation impacts of the cocoon processing could be mitigated by moving to renewable energy sources such as photovoltaic, solar thermal, or wind power. Moving to the use of solar dryers for silkworm cocoons would also be of significant benefit when compared to the use of electric dryers, potentially reducing electricity usage in the cocoon processing phase of production by as much as ten times (Astudillo et al., 2014). Both of these measures would have the additional benefit of reducing carbon emissions and smoke and soot pollution from wood-burning generators.

Reducing the impact of mulberry cultivation would make a very significant difference to the environmental sustainability of the industry. This could be done via several strategies, all of which would work in combination and all of which could be applied in developing nations without requiring large input in the form of infrastructure. The most 'high-tech' of these strategies is the selection and breeding of mulberry varieties for local climatic and soil conditions as well as yield would allow farmers to decrease their irrigation levels and their fertilisation and pesticide application levels. projects to breed more productive mulberry varieties are already ongoing in Bengal (Doss et al, 2011b), and adding local climatic factors to the selection criteria would be a simple and effective method of increasing the sustainability of silk production. New varieties would take time to filter out to rural farms, and to grow to a useful and productive size, but it would nonetheless be a beneficial step to take.

There is also the opportunity to research and implement multi-species cropping systems to increase the resiliency of mulberry cultivation. Intercropping multiple species can be beneficial in controlling plant diseases and insect pests (Van Mele & Van Chien, 2004), and may offer other benefits. For example, intercropping ice-cream bean trees (*Inga edulis*) with the timber tree *Terminalia amazonia* produces better growth than a monocultural stand of Terminalia amazonia due to the nitrogen fixation provided by the *Inga edulis* trees (Nichols & Carpenter, 2006). It appears that no research has been done on intercropping using mulberries, but the broad utility of *Morus* species indicate that any such research would be of use to many farmers in many different contexts and industries.

More immediate gains could be achieved by implementing fertiliser application recommendations based on soil testing (Astudillo et al., 2014), and using more organic fertilisers. Soil testing is not available necessarily to all farmers, but with government assistance in the form of government soil testing programs or subsidised soil testing kits for on farm testing it is quite plausible that the majority of sericulture farms could implement this. It would be in their interest to do so, as lower fertiliser inputs would decrease their operating costs. With a small government investment in education, farmers could be encouraged to use organic fertilisers (compost and manure from livestock) in place of some or all of the chemical fertilisers they would otherwise be using. This change would again reduce operating costs for farmers, and may reduce fertiliser runoff. The use of organic compost might also act as a motivator for farmers to compost their organic wastes on farm, which in and of itself would increase the sustainability of silk production. This compost could be used not only to fertilise the mulberry trees, but also to grow vegetables or mushrooms as a secondary cash crop or for the farmers' own use.

As an alternative to composting or vermicomposting, anaerobic digestion of organic wastes could be used to generate biogas. Anaerobic digesters are used widely in India (Astudillo et al., 2014), and increasing the use of this technique to manage sericultural waste might allow farmers an additional income stream while decreasing waste streams from the silk production. The generation of biogas from anaerobic digestion of organic waste not only reduces carbon emissions or waste streams directly, it also reduces carbon emissions form the fossil fuels which would otherwise be burned (Battini, Agostini, Boulamanti, Giuntoli, & Amaducci, 2014), including natural gas. This means that there is a not insignificant motivation for governments to encourage the use of anaerobic digesters to produce biogas.

The sustainability and environmental impact of fibre production industries is of similar importance to that of the more widely considered food production industries. Although the silk industry currently has a higher impact than many other fibre production industries, there is no reason why it could not become one of the most sustainable of agricultural industries. Silk production is labour intensive, but does not produce high levels of toxic waste, instead producing organic and easily handled waste products. The main impacts, fertiliser and pesticide runoff form mulberry cultivation, are similar to the impacts of most plant-based agriculture and are manageable using similar techniques. Hansen (1996) said that the definition of sustainable agriculture as an agricultural enterprise which could continue over time is measured by long term trends and by resiliency to sudden changes. Although future trends remain unknown, the history of the adaptability of the silk industry leaves one hopeful regarding its ability to change sufficiently to become and remain sustainable in the modern context. The ongoing demand for silk fibre certainly provides a motivation for producers to do so.

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