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Life Cycle Analysis of Cumulative Energy Demand on Sericulture in Karnataka, India

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Abstract

The environmental impact of textile production is an area of increasing focus for both regulation and consumers. Life Cycle Assessment (LCA) is a framework to determine actual and potential environmental impacts associated with products and services and identifying efficient opportunities for reducing burdens. With few exceptions, such LCA data is available on the primary production of textiles. Despite its high profile, no prior LCA studies of sericulture and silk reeling have been performed.

We conducted an LCA of silk yarn production in India using data from a pilot survey performed in Karnataka state. The study focused on cumulative energy demand (CED). Our results indicate that on a mass flow basis Indian silk is a highly resource intensive product. Calculated CED values are above 1800 MJ/kg, significantly higher than for comparison fibres. Survey results further indicate that most sampled farmers diverge from guideline values in fertiliser application. The identified hotspots of energy use in irrigation and reeling energy use suggest that these would be effective areas of focus in increasing silk sustainability.

Keywords: Raw silk production, Silk reeling, Cumulative energy demand

Introduction

Environmental concerns are increasing over the ecological production costs of fibre materials for textile, composite and other applications. Embodied energy, water consumption, resource use and ecological impact of textile fibre production, processing and disposal are of increasing concern to consumers, manufacturers and government. The potential deleterious impacts of large-scale cotton production on for example water resources are well studied (Chapagain et al. 2006) and undoubtedly influence consumer purchasing decisions. Studies argue the relative merits of manmade fibres over natural fibres or vice versa (Cherrett et al. 2005). In most cases, such studies use the Life Cycle Assessment (LCA) methodological framework.

While silks are commonly perceived as being wonderfully sustainable materials they should be no exception to rigorous analysis taking into consideration fundamental ecological concerns about issues such as water use and heating costs. Hence it is surprising that as yet there has been no cradle-to-gate LCA study of the environmental impact of silk production although specific Material Flow Analyses have been performed on the Indian silk reeling sector (Shenoy et al. 2010). The objective of our research presented here is to examine the energy requirements of raw silk production processes in the context of the quantitative LCA methodology. Cumulative energy demand (CED) is used as indicator of energy requirements. CED covers the energy requirements through the life cycle, including direct and indirect uses of energy, of most relevant processes and sub-processes that go into the manufacture of the material. It has been widely use as indicator and it is considered a good "entry point" into LCA (Hischier et al. 2010).

Life cycle assessment is an internationally standardised method to evaluate the impact of a good or service. It quantifies relevant emissions and resources consumed during the life cycle of products and their potential impact to health and environment (European Commission, 2010). It is widely used as a decision support tool for various purposes. It has been used to assess the trade-offs of production methods (i.e. organic vs conventional farming) (Meisterling et al. 2009), identify environmental hotspots (Roy et al. 2008) and in green public procurement (European Union, 2011).

The data from the different stages of the product is collected and aggregated according to standard methodologies into relevant impact categories. The choice of which impact categories to study depends on the purpose of the study. Commonly included for textiles are cumulative energy demand (CED), global warming potential (GWP) or water use (Shen et al. 2010).

The LCA can cover all the stages of the life cycle, production, distribution, use and end of life (cradle to grave studies). The boundaries of the modelled system depend on the extent of the life cycle studied. We have focused on the production side (cradle to gate) of silk as it is the most distinctive part of the life cycle and a first LCA of silk dying is available (Sara & Tarantini, 2003). When LCA is used to compare different production systems or products, care should be taken assuring the consistency of the datasets, as not all studies use the same methodologies or consider the same boundaries (Bessou et al. 2012). Ultimately the applicability of the LCA will be determined by the scope of the study, its intended application, and the extent to which hotspots and inefficiencies in production are identified.

A LCA requires data collection of different flows of energy and materials in and out of the production system, compiled in a life cycle inventory (LCI) characterizing different process and materials. Databases such as Ecoinvent compile thousands of common datasets that can be used as background data for specific processes concerning silk production. Most of the available data refers to Europe, while silk is mainly produced in a completely different context. Thus primary data from silk producers was required as well as adaptation of current datasets.

Silk is a natural proteinous fibre, which has been used in textile manufacture for at least 5000 years. Over 90% of commercially produced silk is extrusion spun by the domesticated Chinese silkworm *Bombyx mori*. This is a monophagous insect whose diet is restricted to the leaves of mulberry plants. Therefore inherent in silk production or 'sericulture' is the growing of mulberry. Broadly there are two races of silkworms. Those originating from the temperate regions of China are called *bivoltines* while their more tropical relatives are called *polyvoltines* or *multivoltines.* The bivoltines produce better silks but are also susceptible to environmental stress and diseases when compared to the poly-voltines. Sericulture in the Indian subcontinent, probably because of its typically higher temperatures compared to China's traditional silk regions, uses either polyvoltine or crossbreed (hybrid) crosses between poly- and with bivoltines. Such hybrids have an enhanced capacity to endure the warmer climate in addition to being more disease resistant (which in warmer climates are a bigger threat) as well as offering a higher silk yield and better silk quality than pure polyvoltines.

Consequently in India the production of bivoltine silk remains as low as 5-10% in spite of ambitious promotional efforts by the government.

With an annual production of 130,000 metric tonnes in 2009 (Central Silk Board 2011), silk constituted 0.2% of the total global fibre produced and 0.5% of the total of natural fibres. While silk's current production volumes are relatively small, the increased interest in tough composites, biodegradable composites, sustainable materials and biomimetic high performance materials indicate that silk has the potential to play an important role in future advanced materials. Silk fibre's superb mechanical properties and its outstanding qualities as a textile are well known (Vollrath and Porter 2009). However in order to count as a 'fibre of the future', silk's environmental impact must be better understood, i.e. fully quantified, for a true comparison with man-made fibres and other substitutes. Hence the importance of quantifying the resources embodied within silk fibres. After all, an obvious ecological benefit of silk relies on it being renewable and biodegradable.

While the green revolution has had a huge effect on yields in all agriculture, the fundamentals of silk farming and reeling in India have changed little since the industrial revolution (Ganga 2003a). Mulberry bushes are cultivated until they are old enough for harvesting of the leaves i.e. typically 2 years in tropical conditions (Ganga 2003b). These leaves are then fed to silkworm larvae. Each newly hatched larva eats about 23g of leaves over a period of about 28 days to become fully grown when it is ready to spin silk for its cocoon. Silk dope (fluid) is produced by the twin silk glands and extruded through the spinneret within the mouth of the silkworm. The double filament silk fibre (i.e. a bave consisting of 2 brins) is spun up to lengths of 1600m into a protective shell or cocoon. The cocoons are harvested and can be sold at a central market to reelers or reeled in-house. Reeling requires boiling the cocoons in water, usually in the presence of alkali or a detergent, in order to soften and partially dissolve the sericin protein which binds the fibres together to form the tough cocoon shell. Softening enables brushes to find and pull the end of the silk filament. The free silk ends of a few cocoons are attached to a reeling machine and unravelled at about 100m/minute. Typically 9 baves are thus collected and twisted into a silk thread, but depending on the quality of the silk as well as the thickness (denier) of the yarn required there can be more or less baves used for the thread reeled. The reeling machine may be foot powered semi-automatic or automatic. 'Charka' or handreeling produces lower quality silk and constitutes a declining proportion of Indian production. It is not considered in this study. The reeling process results in a consolidated yarn called 'raw silk' as well as waste products in the form of waste silk and the pupae. Much of the waste silk can be re-reeled into the raw silk in order to boost productivity; however this is at the cost of quality. The pupae are sometimes sold as fertilizer or fish food, being high in protein and fat. Indeed, ancient Chinese sericulture was often associated with pisciculture with the pupae feeding the fish and the pond mud fertilising the mulberry trees.

At each stage inputs in the form of materials and energy contribute to emissions into the air, the water and the land in the form of co-products and waste. Although beyond the scope of this study, it is important to note that most of locally relevant emissions of present-day sericulture consist of chemical run-off into ground water and drain systems. Capturing, purifying and recycling this water back into the process is possible and should be integrated into modern sericulture. Co-products (leaves, dead worms, pupae, waste silk, etc) are generally used as compost in a closed loop or sold into external processes.

Methods

Goal and Scope definition:

The goal of this study is a first characterization of the environmental performance of Indian silk production concerning energy use, as well as the identification of potential improvements to the process. Using the Life Cycle Assessment methodology as defined by ISO 14040:2006(E) (ISO 2006), this study performs a cradle-to-gate analysis of cumulative energy demand (CED) in raw silk. The functional unit is 1kg of reeled raw silk. CED during distribution, use and disposal of the functional unit are considered out of scope. CED in production of fertilizers, disinfectants, consumables and pesticides is in scope but energy from the manufacture of asset classes (e.g. pumps and ploughs) is excluded. Solar energy content in mulberry and extra energy required by draft animals was not considered. Figure 1 illustrates the production stages of silk fibres

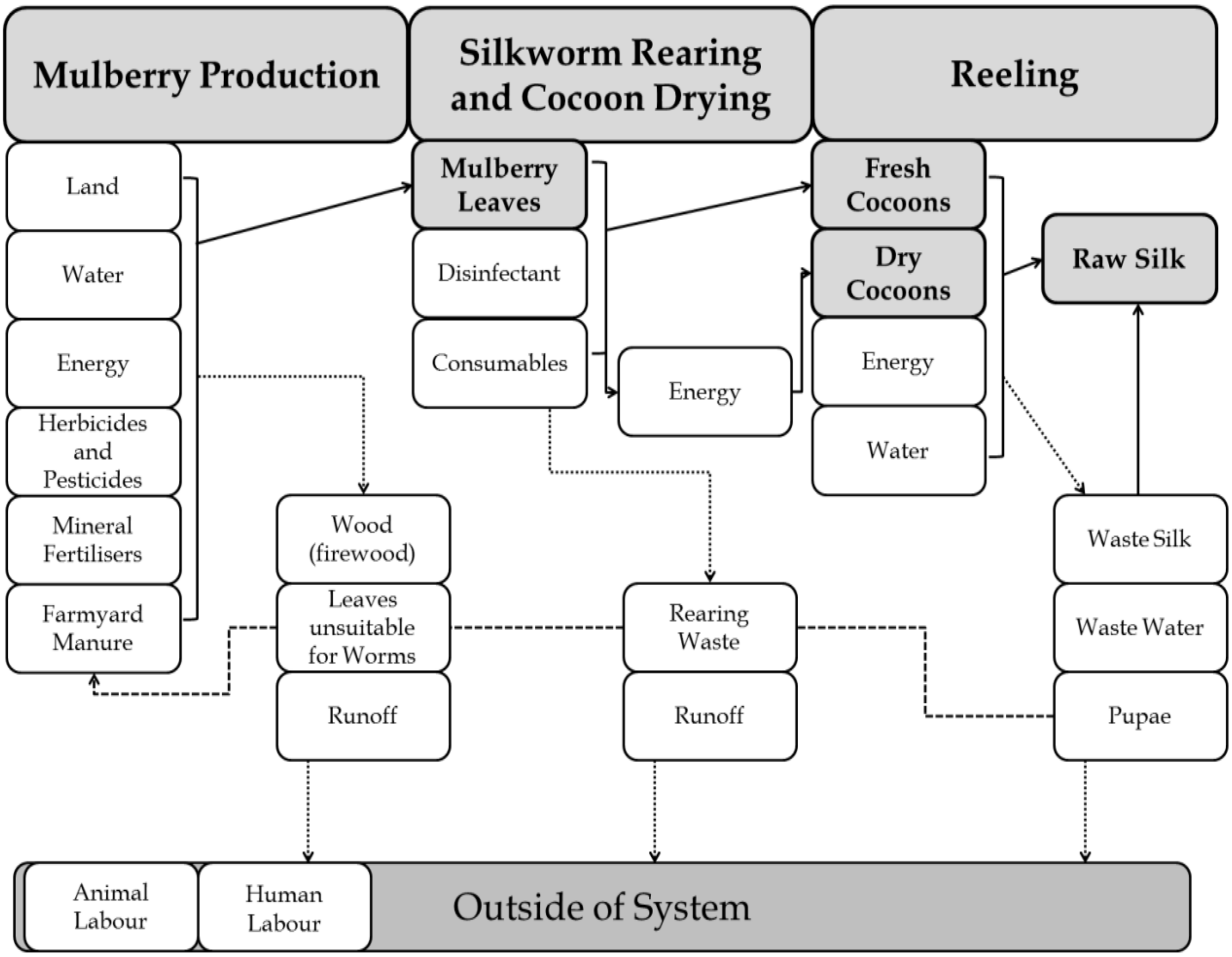

Figure 1 - Mass and energy flow diagram indicating the flow of mass in the production of raw silk. Solid lines: primary inputs; dotted: waste and co-product flows

Life cycle inventory (LCI):

In order to compile and quantify inputs for raw silk, the production process was broken down into two logical subsystems: production of the mulberry leaves and cocoons, and production of raw silk. Two inventory questionnaires were drawn up by GK Rajesh (see Appendix 1), one for the farmers and one for the reelers. The questionnaires were taken independently to 20 farmers and 20 reelers and read-out to them in order to mitigate problems with illiteracy; all verbal answers were transcribed for the analysis. The farms were located in the village of Varuna, Mysore Taluk, Mysore District, Karnataka State. The reelers were located in Ramanagaram town of Ramanagaram district, Karnataka State. This area was chosen as it is representative of the major silk producing state in India. Data was collected in July 2011.

Background Life Cycle Inventory data for many non-OECD countries is lacking (Wernet et al. 2010). That lack of specific Indian data within Ecoinvent required the adaptation of processes from alternative sources – e.g following the method of Itten et al for electricity generation (Itten et al, 2012). Point-source emissions in particular are not directly comparable to those of OECD countries, even when an adjustment factor is applied. Certain impact categories in broader assessments such as eco-indicator99 will thus not be reliable without further study of local conditions and inputs. This issue is significantly less pronounced for CED calculations, and Ecoinvent LCI data was used to calculate the CED for manufactured inputs.

Allocation was solved by system expansion. Co-products as silk waste were not considered for this study, as they have a much lower value than raw silk.

Results

Figure 2 illustrates the flow of energy through the raw silk production process. For simplicity those processes that constitute less than 5% of the CED have been omitted from the flow diagram. The thickness of the red line indicates the relative value of CED for the product flow demonstrating that the energy consumption of raw silk production is close to equally divided between cocoon production (47%) and heat for the cocoon cooking process (51%). Compost use and compost production almost balance each other out (174kg used vs. 144kg produced per kg of cocoons) with the difference being made up in farmyard manure.

As with many other agricultural products the principal energy costs of cocoon production are in the manufacture of the fertilisers and in irrigation. High yield varieties of mulberry such as V-1 will efficiently utilise fertiliser in applications of up to 375 kg/ha/year. Nevertheless, the average consumption of nitrogen in the fertilisers used by our correspondents was 520 kg/ha/year, well above recommended values.

The quantities of any pesticides used (under 0.04kg/kg raw silk) makes their contribution to embodied energy calculations negligible despite their being predominantly organophosphates. Unusually for most agricultural products, the weed management of mulberry bushes uses little or no energy as no herbicide application or mechanical weeding was undertaken with this permanent crop. Labour required in sericultural activities in India is largely supplied by human or animal power. A substantial part of weed management in Indian sericulture is done either manually or by oxen-drawn plough. Illustrating the early development stage of LCA in non-OECD countries, there is currently no established LCA methodology for the use of draught animals in agriculture. We note that in our examples of sericulture all leaf picking was performed by hand and all leaf transportation to the silkworm rearing shed was by animal drawn cart or by humans carrying the loads themselves.

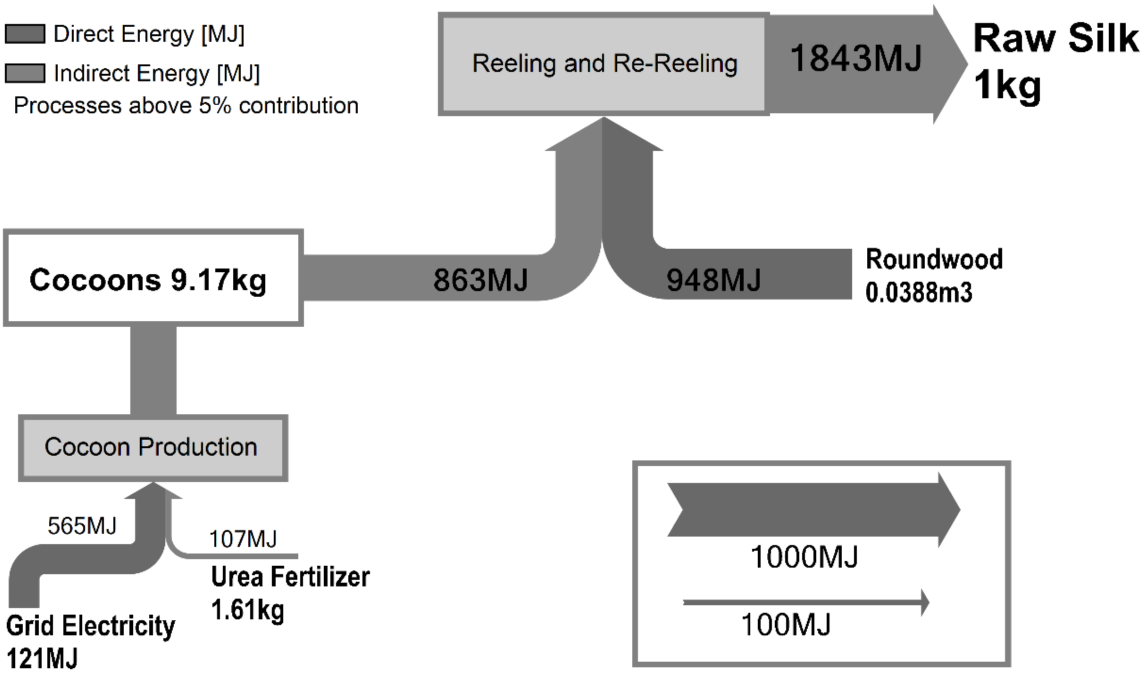

Figure 2: Mass and energy flow in silk production. Mass values and contribution to energy demand are indicated at the top of grey process nodes. Line thicknesses and arrows indicate relative size and flow direction of cumulative embodied energy

In all cases examined, some form of irrigation was used. This took the form of either a tube-well driven by an electrical or diesel pump, or a canal system. Energy consumption as a result of irrigation constitutes approximately 32% of the embodied energy in our example, across irrigation systems. The average electricity used in irrigation was 3130 kwh/ha/year.

During the silkworm rearing stage, the silkworm larvae are kept in rearing sheds with electrical lighting. In the prevalent tropical climate, a well-ventilated rearing shed is sufficient to keep the microclimate at optimum temperature and humidity suitable for silkworms. The climate is especially suitable to the indigenous ‘polyvoltine’ silkworm breeds as they are well adapted to the circumstances. Thus the majority of rearing sheds are structures with large voids in the walls, permitting ample air circulation and thus cutting both the costs of construction and the costs of energy, otherwise required for climate control by artificial means.

These rearing sheds are vigorously disinfected between each cocoon crop (*ca.* 6 times per year) with either one or a combination of bleaching powder, quicklime, parathion and dichlorophos. Rearing bed disinfectants are applied in the form of quicklime and various combinations of herbal extracts with germicidal properties. The beds are usually made of newspaper over a basement made of either nylon or bamboo frames. The newspaper is a consumable and used in large quantities (1.7kg/kg raw silk). Data for energy consumption for the manufacture of newspaper in India is not available and therefore substituted with European values from the EcoInvent database. While this is a fair assumption, it has been noted (Trudeau et al. 2011) that India's paper & pulp mills tend to be less energy efficient than those in industrialised countries.

In our example, silk reeling was the most energy intensive part of the raw silk production process. Reeling is the process by which the cocoon, in which the silk filament is glued in place by sericin protein, is heated in water in order to soften the sericin to a point where unravelling is possible. Water temperature, hardness and pH are critical factors at this stage. It is generally known throughout the silk reeling sector (Datta and Nanavaty 2005) that the temperature of required heating can be changed with the addition of different salts and ions to the soap solution. Cocoons, being buoyant, need to be submerged in a wire mesh cage in order for the cocoon shell to become permeated and the sericin to soften. This takes approximately 10 minutes at temperatures between 60 and 95°C. While electrically powered (e.g. 2kW heating coil) permeation chambers exist (Arya 2011), in our sample set the reelers heat this water with a wood-burning boiler. Charcoal is then used to dry the silk fibres in re-reeling. It is common practice for reelers to produce it in-house from purchased wood (Dhingra, 2003). The wood is locally sourced *Eucalyptus, Neem, Acacia, Tamarind,* etc. In some cases refuse wood shavings from timber mills are also used. Given the desirability of dried wood for the reelers, it is usually air dried. We assume average equilibrium moisture content based on published values (Simpson, 1998).

Reeling machines are either hand driven, semi-automatic or automatic. Hand driven devices require the cocoons to be reeled at 65° – 80°C and 180 - 530metres/minute semi-automatic: 30° – 45°C and 50 – 80metres/minute; automatic: 30° - 45°C and 120 – 200 metres/minute(Datta and Nanavaty 2005). The choice of reeling device therefore has direct implications regarding the embodied energy of the raw silk as well its quality.

Co-products in the form of pupae, waste silk, leaves, stems and dead worms are sold or used as fertiliser and compost.

Discussion

Table 1 - Energy Use per kg silk

	MJ	**%**
Direct Energy		
Wood	948	51%
Electricity	591	32%
Indirect Energy (fertiliser)		
N	168.8	9%
P	94.2	5%
*K**	8.45	0%
Remaining processes	28	2%
Total	**1843**	

Table 1 details the breakdown of the energy inputs into silk production into direct and indirect forms. Under existing practice, direct energy input accounts for a significant majority of total energy use (84%) while indirect energy from the manufacture and transport of chemicals, consumables etc accounts for 15%. Electricity, primarily from powering irrigation pumps, constitutes just over 32% of the total embodied energy

Bombyx silkworms have been selectively bred for millennia to exclusively forage on the leaves of mulberry *Morus alba* (Ganga 2003b). One of the reasons for the co-domestication of this specific plant and the moth might well be the relatively high (15

-28%) protein content of mulberry (Sánchez 2000). Thus mulberry leaf compounds have become the key 'forage' for the silk worm and its silk gland in order to be able to produce the nitrogen-rich proteins fibroin and sericin required in such large quantities for the animal's silk output. Clearly, the high nitrogen content of the leaves requires good soils and fertilisation.

Put into the context of the functional unit used here, this equates to 2.9 kg nitrogen per kg raw silk produced. This very high and if not counter-productive then certainly unnecessary application of nitrogen may well be attributable to excessive application of fertilisers heavily subsidised by the Indian government (Gulati and Narayanan 2000). Indeed, it has been noted amongst Indian agronomists (Singh 2000) that loss in soil fertility as a result of over-fertilisation has resulted in further over-fertilisation compounding the problem. We note here also that several farmers in our sample did not use any urea, substituting more costly ammonium sulphate. This unexpected result is likely due to bottlenecks in supply, and may partially account for observed fertiliser application patterns. The energy cost of farmyard manure, and its production, while added in high quantities did not contribute greatly to the overall embodied energy of raw silk. This was primarily due to the closed loop production of this organic fertiliser later on in the process.

A stock-pruned mulberry garden takes just 45 days to grow back in full foliage, and can produce up to 70 tons of leaves per hectare (Yadav, 2004). Recommended values from moriculture literature (Ganga 2003b) depend on soil type and rainfall but a reasonable recommendation under irrigated conditions for the ruling mulberry hybrid variety V-1 is NPK of 350:140:140 kg/ha/year. Our data shows that cocoon farmers are applying NPK in a ratio of 479:443:132 kg/ha/year. This is partly due to lack of information on best practice on part of the farmers and partly due to prevalent government subsidies in the agricultural sector in India.

The average electricity used in irrigation was 3130 kWh/ha/year, which compares to 1600 kWh/ha/year for the rest of agricultural India (Lall et al. 2011). These relatively high values can be attributed to farmers being able to avoid payment for electricity used in agriculture, and so have little incentive to use their pump systems economically. It may be argued that if they had to pay for the energy used, farmers would find it unprofitable to engage in agriculture – be it sericulture or otherwise (Lall et al, 2011). Subsidies for fertiliser and electricity are linked to the inefficient input use observed in this sample (Planning Commission, 2006). This results not just in excessive energy use, but causes eutrophication and may damage long-term soil productivity (Vijayan et al, 2007)

Cooking the cocoons is one of the primary energy consuming (51%) processes during the production of raw silk. The extent to which the wood has dried out, and therefore its calorific value, is an important criteria for the reelers as it dictates the cost of extractable heat from the wood and the amount needed. However, with the relative humidity of Karanataka State (95% in the monsoon season), the equilibrium moisture content of exposed wood can reach as high as 20% (Reeb 1997), decreasing the recoverable heat value. This would suggest that the burn efficiency of the wood drops significantly in the monsoon season, driving up wood consumption. Given the potential impact this will have the embodied energy it must be argued that more data and analysis is required to realistically estimate the energy inherent in reeling and re-reeling.

To alleviate the significant fuel costs and environmental burdens of wood burning stoves, Dhingra *et al.* developed a gasifier based silk reeling oven which, by converting wood into syngas (H_2 and CO). Heat conversion is up to 46% more efficient and greater control of the water bath is possible, which in turn leads to higher quality silk (Dhingra et al. 2003). This shows that appropriate technological innovation can make a substantial contribution to energy efficiency. Through implementation of existing technologies and economies of scale it is possible to drastically reduce the energy consumption during this critical process in silk manufacturing.

Fully automated reeling machines used predominantly in China use electrical elements to heat the water in a closed boiler as well as massively parallelising the reeling process. This compares with traditional hand-reeling or semi-automatic reeling machines, like those used by the reelers in this study, in which the water is heated under a open fire and in an open basin, resulting in heat and water inefficiencies. However, electricity is a very inefficient way of producing heat, while traditional boilers are based on a renewable resource. Further analysis of both technologies under a LCA framework will clarify the tradeoffs involved.

Efficient use of co-products can substantially improve silk production sustainability. Twigs from rearing beds can be fed to cattle, mulberry shoots can be used as firewood, pupae are an excellent feed in aquaculture and chicken rearing (Jintasataporn, 2012). Commercial applications of sericin would be especially advantageous as is currently not utilised by any reeling operators in our sample. Lastly, other technologies under development such as genetically engineered silkworm which spin directly reelable fibres rather than cocoons (Vollrath and Woods 2011) and additives and processes to water to soften the cocoon at lower temperatures show great promise in further reducing energy requirements.

The energy cost during the process of fibre extrusion from the silk gland can be calculated (Holland et al. 2012) and compared with polyethylene. Formation of the fibrils (building blocks of the polymer fibres) is 10 times more energy efficient in silk than for polyethylene. This is due to the lower shear rates at which silk fibrils form in comparison to those of polyethylene. Also, polyethylene requires 100 times the energy as a result of the need to melt it before it can be spun. On the other hand silk is spun from the liquid dope at room temperature. Overall, therefore, silk is 1000 times more efficient in its energy of formation than polyethylene.

Two lessons follow: Firstly, engineers looking to develop low energy technologies for fibre formation would do well to examine silk. Secondly, the silk industry needs to optimise three specific sub-processes in order to minimise energy costs: fertiliser usage, irrigation systems and unravelling. It is the unfortunate but necessary process of unravelling the cocoons as well as the practice of fertilising and irrigating mulberry that results in a higher cumulative energy demand.

Table 2 - Energy in fibres MJ/kg

Silk (this study)	1843
Nylon	260[1]
Polypropylene	86[1]
Viscose	169[1]
Cotton Yarn	180[1]
Wool (unproc)	118[2]

1: Ecoinvent; 2: Barber & Pellow 2006

Our investigation is a first study of the subject and therefore lacks the breadth and width of a full study. It is thus not comprehensive enough to make conclusive comparisons. It is nevertheless informative to compare the calculated embodied energy in raw silk with other fibres (table 2), bearing in mind regional differences - for example Steinberger et al. found Indian cotton production is between two and four times more energy intensive than US cotton, a difference mainly attributed to poorly regulated groundwater irrigation. (Steinberger et al. 2009).

Conclusions

The value of sericulture for rural development potential is unquestioned, and few other agriculture activities compare in providing gainful employment in areas where agricultural land is scarce. This results in the sector being heavily supported by central and state governments. Moreover, in some states in India silk farmers form an effective pressure group, and have secured extensive subsidies for primary inputs such as fertiliser and electricity used for irrigation. Together these two inputs account for over 45% of the embodied energy in the final product in our study. The reeling industry in Karnataka does not receive the same level of subsidy farmers do, and the reelers operate on a far more independent and entrepreneurial basis, with low margins. This industry is therefore driven by economics and should be interested in more energy efficient processes (e.g. gasifier stoves) (Dhingra et al. 2003) if the return on investment can be demonstrated, capital costs are not prohibitive, and extension services are provided to increase technological awareness.

While it is outside the scope of this study to contrast the embodied energies calculated with figures with those of other silk producing regions, reports from Chinese silk producing areas (Bian 2011), indicate that Indian silk reeling is more energetically expensive. That being said, mass flow is not the only standard by which the environmental impact of textile products can be compared. It is worth bearing in mind that silk is a high-value product without true substitutes. Despite its small market share it occupies a unique place in textile markets, and commands a significant price premium. Indian prices as of Feb 2013 are 7.5 and 11 times higher per kilo for silk than for nylon and cotton, respectively (Ind. Min. Tex., 2013).

The sustainability of silk is often considered a selling point for this ancient and valuable material. Despite the sample size limitations inherent in a pilot study, our results research suggest that with regards to energy consumption, current cottage industry production of this fibre in India has some way to go before it competes with most manmade fibres on this metric. Fertilization, irrigation and wood consumption are the identified environmental hotspots. LCA can be successfully used to identify the most effective ways of improving the production taking into account the whole production cycle.

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representative of the Indian silk industry as a whole. More extensive research will be needed for a full characterization of Indian silk.

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