Final Report

Energy Use Life Cycle Assessment for Global Cotton Production Practices

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Executive Summary

The goal of this project was to use Life Cycle Assessment (LCA) to quantify the energy required for cotton production over a range of global cotton production practices. Energy use is only one measurement of agricultural sustainability, but represents a method for unifying measurements of a variety of other inputs into agricultural production. The Center for Agricultural and Rural Sustainability at the University of Arkansas developed a model of energy usage by identifying a range of production practices across the globe and using these practices as parameters for the model. The LCA quantified various forms of energy inputs including direct mechanical, animal, and human energy required to produce a unit of raw cotton (expressed as a tonne or 1000 kg). The LCA also quantified energy embodied in the fertilizer, mechanical components and manure. The production of secondary products (seed, oil, etc.) was analyzed to quantify potential recoverable energy. The model quantifies energy used to perform various cotton production tasks including field preparation, planting, field operations and harvesting.

The average embodied energy of production of a tonne of cotton from the ten regions of the world ranges from 5,600 MJ/tonne (North America East) to 48,000 MJ/tonne (South America Non-Mechanized). The LCA of energy associated with use of manure as fertilizers in cotton production clearly demonstrated the large quantity of energy embodied in manure. Quantifying this opportunity cost (where manure energy can be practically utilized, e.g., using manure as a fuel for heating or cooking), increases the expressed embodied energy of cotton production of those systems almost tenfold. The LCA of net energy costs of production, measured as embodied energy minus potentially recovered energy (cottonseed oil and meal), showed that six of the ten regional production scenarios have the potential to be net energy-producing systems. The most sensitive variables for net energy production for cotton were yield and irrigation.

Introduction

Cotton is grown in warm tropical and sub-tropical climates and is frost sensitive. It has moderate water needs, and a deep tap root (1 m or more). There are documented cases of its cultivation as long ago as 5,000 years (Shishlina et al, 2003; Chowdhury and Buth, 1971). The wild precursors of modern cotton were 33 different species of small perennial shrubs that have been genetically modified through selective cultivation and breeding over 5 millennia into single season row crop varieties. The resulting four primary domesticated species of commercially important cotton are all in the genus *Gossypium*: *hirsutum*, *bardadense*, *arboreum*, and *herbaceum* (Wakelyn et al., 2007). Cotton is an important economic fiber, representing 40 percent of the total fibers consumed in the textile industry in 2004 (Wakelyn et al., 2007). Cotton is also an important feed source; the oil from the seeds is used to make vegetable oil for human consumption, and the cottonseed meal is used for animal feed. Grown across the world, cotton flourishes in areas that are traditionally too dry for other crops. The top four producers (China, India, U.S. and Pakistan) accounted for almost 80% of the world production in 2006 (Altin et al., 2006).

The objective of this project was to determine the energy required to produce one tonne (1000 kg) of raw cotton (including both seed and lint, in the field) across a range of global production practices using a Life Cycle Analysis (LCA). The LCA was structured to compare total (direct plus embodied) energy across 10 geographic regions. Direct energy is energy expended directly by humans, animals, and machinery in production practices. Embodied energy is energy required for the production of fertilizers and the manufacture of agricultural equipment. Two additional scenarios were analyzed with the LCA: energy embodied in manure where it is used for fertilizer, and potential recovered energy from cottonseed oil and meal.

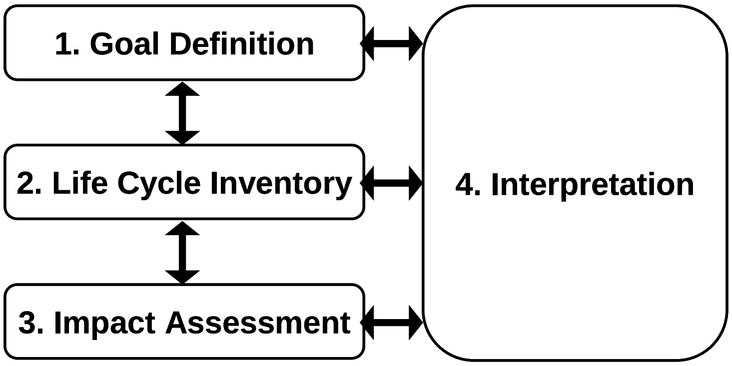
Life Cycle Assessment Structure

Life Cycle Assessment (LCA) approach analyzes complex processes in order to quantify the inputs and/or outputs from a Process Unit (ISO 14040, 2005). The LCA approach covers the life cycle of a process, or beginning-to-end of a process, in a systematic, stepwise process composed of four components (USEPA, 2006):

1) Goal Definition – Define the product, process, or activity being analyzed, including the context and boundaries of the assessment.
2) Life Cycle Inventory – Identify and quantify the components of the process (process unit and associated elements) defined in Goal Definition, including a detailed process flow diagram to frame inputs, outputs, and processes.
3) Impact Assessment – Assess the potential impact from scenarios described in the Goal Definition on the components identified in the Life Cycle Inventory.
4) Interpretation – Evaluate the scenario analyses in the context of the Goal Definition to develop improved understanding and subsequent strategies for process improvement.

The LCA process is iterative and the interpretation can become subjective if the goal definition stage is not explicitly defined (Figure 1). The iterative nature of the LCA process requires rigorous documentation and process discipline to eliminate drifting objectives. The objective of the LCA must be preserved throughout the process. LCAs can become instruments of rationalization rather than objective analysis if the LCA process is not open and transparent. Thus, the process for populating the inventory with data, relating data to processes, and assessing scenarios should be clearly defined and reviewed in order to avoid potential bias.

Figure 1: Life Cycle Assessment Framework (modified from ISO 14040, 2005).



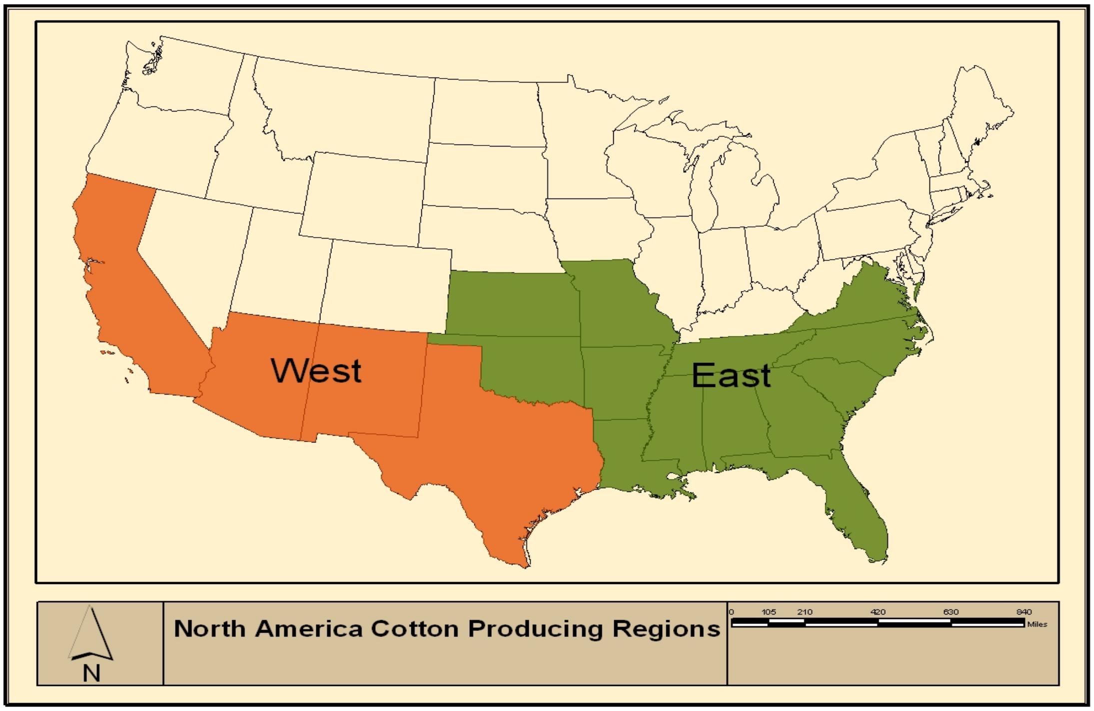
Goal Definition

The project objective was to determine the energy required to produce one metric tonne (1000 kg) of raw cotton (including both seed and lint, in the field) across a range of global production practices using a Life Cycle Analysis (LCA). The goal was to analyze scenarios across ten global production practices to assess energy costs of production for a unit of raw cotton on the ground, not including costs of transport, ginning, or processing. Two additional scenarios were analyzed: energy embodied in manure fertilizer and potential recovered energy from cottonseed oil and meal.

Life Cycle Inventory

For the Cotton Energy LCA the world's main cotton producing regions (North America, South America, Africa, Mediterranean, Asia, and Australia) (Table 1) were categorized into ten production strategies based upon the intensity of mechanization and irrigation used (low versus high). The North American region was divided into separate regions because the western region is predominantly irrigated and the eastern region is not (Figure 2). Such broad generalizations are only accurate at the most coarse level of analysis, so data interpretation must also be at coarse levels. For example, Texas was included in the western region of North America, even though cotton production in eastern Texas is not generally irrigated. Similar generalizations were made for production practices around the world, resulting in ten categories of production strategy by global region (Table 2). These categories are the *Operational*

Figure 2: Cotton Production Strategy Regions of the United States



Units of analysis in the Life Cycle Inventory.

The process flow model for cotton production within each operational unit was characterized as four main tasks*: field preparation, planting, field operations,* and *harvesting*; the *field operations* task was further divided into *irrigation*, *weed control*, *pest control*, and *fertilization* (Figure 3) (International Cotton Advisory Council, 2005). The cotton production tasks and subtasks were characterized by operational unit as mechanical or non-mechanized (animal or human labor), with the exception of fertilization, which was characterized as conventional (inorganic) or manure. Each region represented a unique matrix of production practices, aggregated to represent production strategies globally (Table 2). This regional cotton production energy efficiency was measured in mega-Joules per metric tonne (MJ/Tonne), the SI units for this scale.

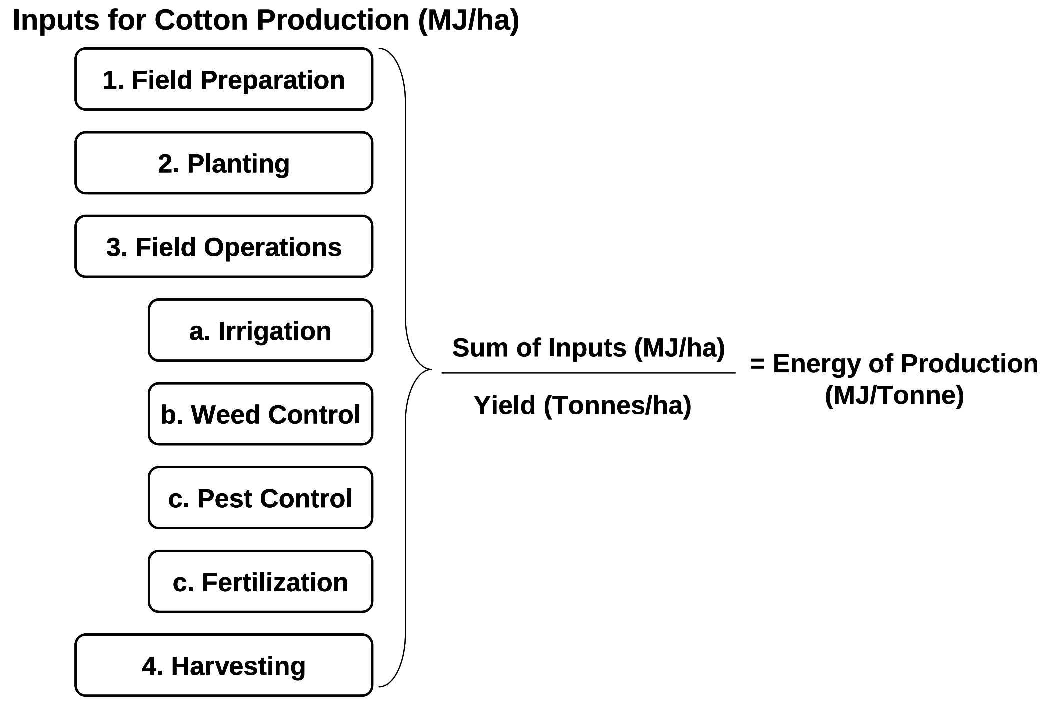
Table 1: Distribution of Global Cotton Production and Percent of Cotton Production, 2006 (USDA, 2006; FAO, 2007).

Region	Production (million tonnes/year)	Percent Total
Asia	15,947	60
North America	5,316	20
South America	1,595	6
Mediterranean	2,126	8
Africa	1,329	5
Australia	266	1

Table 2: Cotton Production Strategies by Region for the Cotton Energy LCA

Region/System	Production Strategy	Irrigation	Fertilizer
North America East	Mechanized	None	High
North America West	Mechanized	High	High
South America Mech	Mechanized	Medium	Medium
South America Non-Mech	Non-Mechanized	Medium	Medium
Australia	Mechanized	High	High
Mediterranean - Mech	Mechanized	Medium	High
Mediterranean - Non-Mech	Non-Mechanized	Medium	Low
Asia - Mech	Mechanized	High	High
Asia - Non-Mech	Non-Mechanized	Medium	Medium
Africa - Non Mech	Non-Mechanized	High	Low

Figure 3: Cotton Production Model for the Energy LCA



The energy associated with each task was determined from a review of contemporary literature. The types of energy incorporated into the model include both direct and embodied energy. Direct mechanical energy for each task was calculated by multiplying the estimated fuel requirements (for tractor or harvester) to complete a task (volume of fuel per unit area of production), by the energy per unit volume of fuel (i.e., 37.6 MJ/L for diesel fuel) (Griffith and Parsons, 1983; Larson and Fangmeier, 1978). The volume of diesel fuel required per task was estimated from peer-reviewed and industry literature (Oren and Ozturk, 2006; University of New Mexico, 2003; Tsatsarelis, 1991; Turn et al., 1988; Larson and Fangmeier, 1978).

Direct Energy. Direct mechanical energy for irrigation was estimated using one of three methods: (a) energy values directly from the literature (Oren and Ozturk, 2006; Yilmaz et al, 2004; University of New Mexico, 2003; Wanjura et al., 2002; Tsatsarelis, 1991; Turn et al., 1988; Larson and Fangmeier, 1978); (b) energy calculated from volume of diesel fuel used (Rogers and Alum, 2007; Rogers et al., 2007; Mississippi State University, 2007; Larson and Fangmeier, 1978); or, (c) energy calculated based on the amount of water needed. The latter method used the Nebraska Pumping Plant Performance method [20] based upon required irrigation amount (depth of water (Oren and Ozturk, 2006; Yilmaz et al., 2004; Munier, 2002; Tsatsarelis, 1991; Turn et al., 1988; Larson and Fangmeier, 1978)), assuming well depth of 30 m and outlet pressure of 276 kPa, to calculate the amount of fuel needed to power an irrigation pump of standard efficiency. Energy equivalents were calculated based on diesel fuel as the energy source (Larson and Fangmeier, 1978).

Direct non-mechanical energy for each task was estimated using the time required to complete a cotton production task for both human and animal labor multiplied by the energy output per unit time for humans and animals (Lawrence and Smith, 1988). Human labor was estimated to provide 1.08 MJ/hr sustained throughout a 10-hour day (Hicks, 1997). Animal labor was assumed to be oxen; energy input (as feed) was derived by dividing the energy output (MJ/hr) by the efficiency of conversion (Singh et al., 2002).

Embodied Energy. The embodied energies associated with the production of fertilizers and manufacture of typical farm equipment was estimated for each mechanical task. The embodied fertilizer energy in cotton was calculated by multiplying nutrient demand (mass of nutrient per unit mass of cotton) by the embodied energy of the fertilizer itself (energy per unit mass of fertilizer) and by the estimated cotton yield (mass cotton per unit area) (Oren and Ozturk, 2006; Richards, 2004; Yilmaz et al., 2004; Griffith and Parsons, 1983; Larson and Fangmeier, 1978). The embodied energy associated with the production of fertilizer was limited to the production of nitrogen and phosphorus; other nutrients contribute comparatively minor amounts of energy, and were not considered in the model.

The embodied energy associated with the production of agricultural equipment was calculated using an economic input-output life cycle assessment model (I/O LCA) (Carnegie Mellon University Green Design Institute, 2007). The I/O LCA model was used to quantify the energy needed to produce agricultural equipment based on the price and the power rating of the equipment. The size of equipment was determined from the Mississippi Crop Budget Generator for Arkansas Budget (Mississippi State University, 2007). The total energy to produce a tractor was amortized over the time the tractor was used to complete a task and the total expected life of the tractor, resulting in an estimate of the embodied energy of farm equipment for a given task. The time the tractor was used to complete an individual task was calculated by dividing the estimated volume of fuel the tractor needed per task by the fuel consumption rate of each tractor (volume of fuel per unit time). Data from the Mississippi Crop Budget Generator were only available for field preparation, planting, and fertilizer application. Embodied energy for weed control and pest control were assumed to be completed by chemical application and use of a sprayer. The embodied energy in a sprayer was assumed to be 25.6% of the diesel energy associated with using the sprayer.

Process Units and Production Strategies. The process units defined production strategies. North America West included the states California, Arizona, New Mexico and Texas. These states represent a warm and dry climate, which is ideal for high yield cotton production, but also require large amounts of water for irrigation. North America East included Kansas, Missouri, Oklahoma, Arkansas, Louisiana, Mississippi, Tennessee, Alabama, Georgia, Virginia, North Carolina, and South Carolina. These states generally have cooler climates and require less irrigation than the west. Fully mechanized production practices were assumed for both North America West and East. The major difference in production energy came from irrigation demand, fertilization demand, and yields. Cotton production practices in North America East were assumed to be non-irrigated which represents the predominant practice. Embodied fertilizer information for North America West came from the nutrient requirements for the United States via the International Cotton Advisory Committee, from Arizona data and the 2005 California Cotton Budget. Yield information for both North America East and West were obtained from the United States Department of Agriculture (USDA, 2006).

The Asian region was separated by mechanical and non-mechanical production practices. Energy requirements for mechanical production were assumed to be similar to that identified for North America. The same requirements were assumed for the following production tasks: field preparation, planting, weed control, pest control, fertilizer application, and harvesting. The production data for non-mechanical production was taken from India (Singh et al., 2002) for the following tasks: field preparation, planting, weed control, pest control, fertilizer application, and harvesting. Energy for irrigation was taken from data for China (Turn et al., 1988). Mechanical irrigation was assumed for both mechanical and non-mechanical practices. Embodied fertilizer energy was derived from nutrient needs and assumed to be conventional NPK fertilizer for mechanical practices and to be manure for non-mechanical practices.

The South American Region was divided into mechanical and non-mechanical production practices. The mechanical production practices were assumed to be similar to mechanical practices in the Western United States. The non-mechanical practices were assumed similar to the non-mechanical practice in Asia for field preparation, planting, weed control, pest control, and harvesting. The irrigation requirements for the South American Region were assumed to be the same as North America West. The yield data was given by the Food and Agriculture Organization for each South American country (FAO, 2007).

Yield was a highly variable input parameter for the LCA; South America exhibited the largest range of yield values, from 0.13 to 3.0 tonnes/ha. In order to differentiate between production strategies, operational units (countries) were divided to either mechanical or non-mechanical production practices based upon their reported yield; yields of 1.5 tonne/ha or greater were assumed to be mechanical, and yields less than 1.5 tonne/ha were assumed to be non-mechanical. For mechanical production practice, fertilizer application was assumed to be conventional fertilizer and calculations were based on yield-estimated demand. In countries assumed to be using a non-mechanical production practice, fertilizers were assumed to be applied in the form of manure. Embodied energy of manure was calculated as a separate scenario, since manure is often considered a by-product of animal labor.

The production tasks for Australia were assumed to be the same as for the Eastern United States. Yield data for Australia were obtained for both Queensland and New South Wales, the two main cotton producing regions in Australia (Australian Bureau of Agricultural and resource Economics, 2007). The embodied fertilizer energy was calculated based on the use of conventional fertilizer (Cotton Australia, 2007).

For the Mediterranean region both mechanical and non-mechanical production practices were assumed. The production tasks were assumed to be the same as North America for all tasks excluding harvesting and irrigation. Harvesting for the semi-mechanical practice was assumed to be manual. Additional semi-mechanical production task energy requirements for field preparation and irrigation were taken from Turkey

(Yilmaz et al., 2004). The non-mechanical production strategy was assumed to be similar to Asia. The yield data were separated into mechanical and non-mechanical practices based upon yield.

Non-mechanical production practices were assumed for Africa because of generally low yields. This is a significant source of uncertainty, and should be addressed with more detailed analyses in the future. The production tasks were assumed to be the same as non-mechanical Mediterranean regions with the exception of irrigation (Pesticides Action Network UK, 2002). A separate analysis which includes the energy content available in the manure was performed to illustrate the opportunity cost of using the manure as fertilizer rather than an energy source in production strategies for regions like Africa.

Life Cycle Uncertainty Analysis

The LCA model was constructed in Microsoft Excel (Microsoft Corporation, Redlands, Washington) with an uncertainty analysis add-on package, @Risk (Palisade Corporation, Ithaca, NY). This approach insured that all data being used in the LCI were auditable, and that all calculations and assumptions were transparent.

Regional data at the operational unit were analyzed using stochastic methods to propagate uncertainty associated with the literature values. This method allows for the various energy inputs to be used to estimate the uncertainty in the calculated value of the embodied energy per tonne of cotton (Weidema et al., 2003). All parameters in the LCA were represented as probability distribution functions (pdf's). Simple rules for assigning pdf's were applied to reduce bias introduced to the input parameters (Table 3).

Data richness and confidence were ranked from low to high, with specific pdf's associated with each set of characteristics. For a variable with low data richness (<4 data points) and low confidence (source or type of data, extrapolations, etc.), a Uniform Distribution with upper and lower ranges at plus and minus 100 percent of the mean value, respectively, was assigned. For variables with some data (at least 5) a triangular distribution was applied. For rich datasets, the best-fit PDF was determined based upon the Chi-Square test. Monte Carlo simulation with 10,000 iterations was performed on the LCA model and each of the scenarios to produce maximum likelihood estimates of the embodied energy with quantified uncertainty bounds (90 percent).

Table 3: LCI Rules Matrix for Assigning PDFs in Cotton Energy LCA

Data Richness		Data Confidence		
		Low	**Medium**	**High**
	Low	Uniform ±100%	Uniform ±50%	Uniform ±25%
	Medium	Triangle ±100%	Triangle ±50%	Triangle ±25%
	High	Best fit PDF	Best fit PDF	Best fit PDF

Scenario 1: Manure as Energy Source

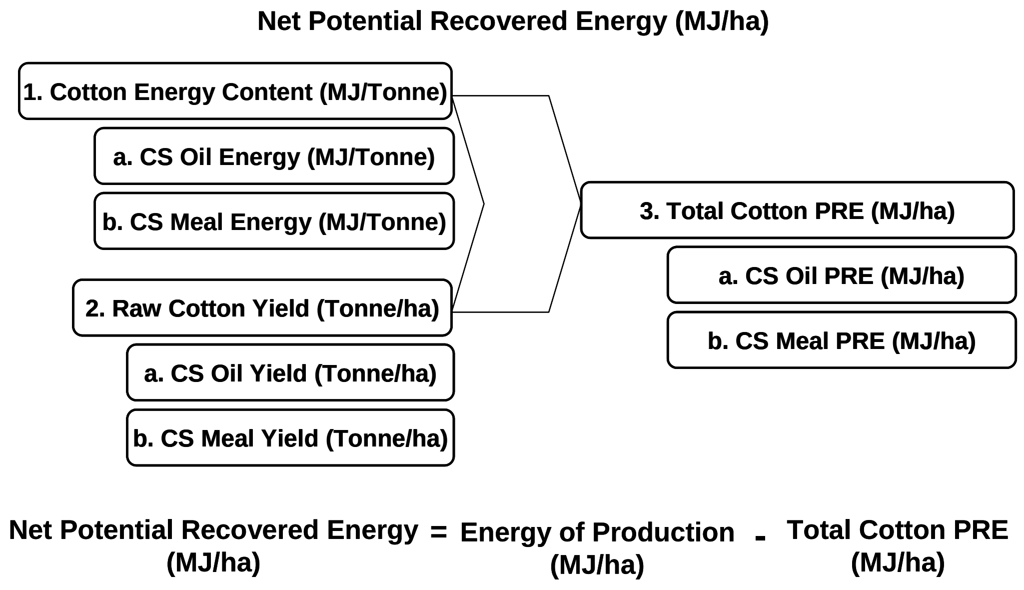
The use of manure as fertilizer was considered a zero net energy cost in the LCA. However, manure from ruminants has high energy content, and is often used as fuel for heating and cooking as well as a binding material in mud and wattle construction. Thus the analysis of energy embodied in a tonne of cotton when manure was used as the fertilizer was performed. The amount of manure applied to a production system (mass per unit area) was estimated by dividing the assumed nitrogen (N) demand of cotton crops in different regions (mass N per unit area) by the nitrogen content of cow manure (assumed 5 kg N per tonne of manure) (Beegle, 1997). The embodied energy associated with manure was calculated by multiplying the mass of manure (per unit area) by the energy content of manure (assumed to be 20 MJ/kg) (Mukhtar and Capereda, 2006). The assumption was made that for production practices using manure as fertilizers, no inorganic fertilizers were used. The potential for autocorrelation between manure as fertilizer and low yields is a concern in this analysis.

Scenario 2: Potential Recovered Energy

Cotton production generates lint, seed, and trash (hulls, stems, etc). These products are separated in the ginning process, but energy from these secondary products of the cotton plant can be recovered (Holt et al., 2000). Cottonseed products include cottonseed oil, cottonseed meal, cottonseed hulls, and linters. Cottonseed oil is used as cooking oil and has potential for use as a bio-fuel (Auld et al., 2006; Karaosmanoglu et al., 1999). Cottonseed meal can be used as a feed for cattle, poultry, and other animals (Holt, 2007; Blasi and Drouillard, 2002). Cottonseed meal can also be used as fertilizer however its acidity limits its usability. Cotton gin trash (linters, hulls, stems, etc) also has energy value (Holt et al., 2000). However, for the purposes of this analysis, Potential Recovered Energy was defined as energy that is readily utilized and commercially viable. Only the recovered energy from cottonseed oil and meal were considered fungible in this analysis.

Potential Recovered Energy (PRE) was estimated by adding the energy of cottonseed oil and meal production (MJ/ha) for each operational unit and subtracting the energy of extraction (processing and separation) (Figure 3). The two methods commonly used to extract cottonseed oil are extraction by crushing mill or extraction by use of a solvent, commonly hexane or isohexane. Generally 15% of the mass of the cotton seed can be extracted as cottonseed oil (Auld et al., 2006; Karaosmanoglu et al., 1999). The average energy value of raw cottonseed oil is 39,600 MJ/tonne (Karaosmanoglu et al., 1999). The energy needed to process the cottonseed and extract the oil was assumed to be similar to that of the extraction of soybean oil:

Figure 3: Method for Estimating Net Potential Recovered Energy from Cotton Production



2,380 MJ/tonne for seed processing and 5,045 MJ/Tonne for extracting the oil (Yi et al., 2006). Thus the net energy from processed cottonseed oil was estimated at 32,223 MJ per tonne of cottonseed oil. The amount of energy recovered from cotton production as cottonseed oil was estimated for each regional scenario by analyzing the energy per hectare of production to reduce the potential of bias from high yield systems. Cottonseed oil and meal production per hectare were parameterized for each region and production strategy (FAO, 2007). The potential recovered energy from cottonseed oil and meal was subtracted from the energy costs of production for each process unit to estimate Net Potential Recovered Energy (nPRE).

Impact Assessment

Cotton production practices vary broadly around the world. Regions within a country can have high variability in cotton practices can be highly variable, based upon infrastructure, topography, climate, culture, agro-economics, and a variety of other factors. However, when the energy required to produce a quantity of cotton is aggregated even at high levels for comparison, as in this study, insights emerge. The opportunity for increasing energy efficiency in cotton production is greatest where underlying production practices vary most – areas such as South America and Africa that do not use predominantly mechanical production practices (Figure 4).

The average embodied energy for production of a tonne of cotton from the 10 regions of the world ranged from 5,600 MJ/tonne (North America East) to 48,000 MJ/tonne (South America Non-Mechanized) (Table 4). The LCA was sensitive to two predominant variables in embodied energy: irrigation and yield. The highest variability within production regions was in the South America Non-Mechanized region and Africa Non-Mechanized regions (Figure 4). The very low yields in these regions resulted in potentially low energy efficiencies of production, based upon parameter estimation in the stochastic model. Highly variable yields translate to highly variable efficiencies. Five of the global production regions required less than 10,000 MJ/tonne to produce cotton; these systems represent efficient production strategies. Two of these production strategies (Asia and Mediterranean) were non-mechanized.

Scenario 1: Manure Energy Analysis. The LCA of energy associated with use of manure as fertilizer in cotton production demonstrates the potential energy embodied in manure (Figure 5). Manure is a common fuel source for many subsistence communities and is a real cost of production. Accounting for this opportunity cost increases the embodied energy of cotton production almost tenfold. For farmers who can utilize the energy content of manure as a fuel rather than expend it as a fertilizer for cotton, the embodied energy in the cotton production may be cost prohibitive. The use of commercial fertilizer as a supplemental source of nitrogen and phosphorus might be cost-beneficial when the true cost of using manure is considered.

Scenario 2: Net Potential Recovered Energy Analysis. Analysis of the area-based energy requirements for cotton production identified four operational unit strategies as most efficient on a per-hectare basis: North America East, South America Non-mechanized, Asia Non-mechanized, and Mediterranean Non-mechanized (Figure 7). The analysis used yield to estimate area-based energy recovery for each operational unit (MJ/ha). Comparison of Figure 6 with Figure 7 illustrates the potential for increased efficiency of production by increasing yields globally.

Cotton production in six of the ten operational units yielded net potential recovered energy (90% confidence) (Figure 7). In four of the ten regions, the mean PRE was greater than the energy required to produce cotton. The data are presented as proportion of total energy of production recovered as PRE for comparability. This analysis suggests that for those regions more energy is extracted from cottonseed oil and meal than is embodied in the overall cotton production. The potential to move the other production strategies to negative net energy production requirements is likely limited by regional variables such as rainfall, crop management practices, and infrastructure for production. Thus, for much of the cotton-producing world, more energy (MJ/ha) is extracted from cotton production than used in the production process.

Table 4: Summary of Embodied Energy of Production of Cotton for Each Process Unit

Region	Production Strategy	Irrigation	Fertilizer	Mean (MJ/tonne)	Standard Deviation (MJ/tonne)
North America East	Mechanized	None	High	5,667	962
North America West	Mechanized	High	High	14,081	5,176
South America Mech	Mechanized	Medium	Medium	24,258	6,090
South America Non-Mech	Non-Mechanized	Medium	Medium	48,205	63,488
Australia	Mechanized	High	High	8,249	2,188
Mediterranean - Mech	Mechanized	Medium	High	9,114	3,992
Mediterranean - Non-Mech	Non-Mechanized	Medium	Low	6,901	1,350
Asia - Mech	Mechanized	High	High	13,043	5,658
Asia - Non-Mech	Non-Mechanized	Medium	Medium	9,989	18,275
Africa - Non Mech	Non-Mechanized	High	None	44,942	25,484

Figure 4: Embodied Energy of Cotton Production (MJ/tonne). Cross-marks represent means, and upper and lower ends of vertical bars represent the upper and lower 90% confidence intervals, respectively.

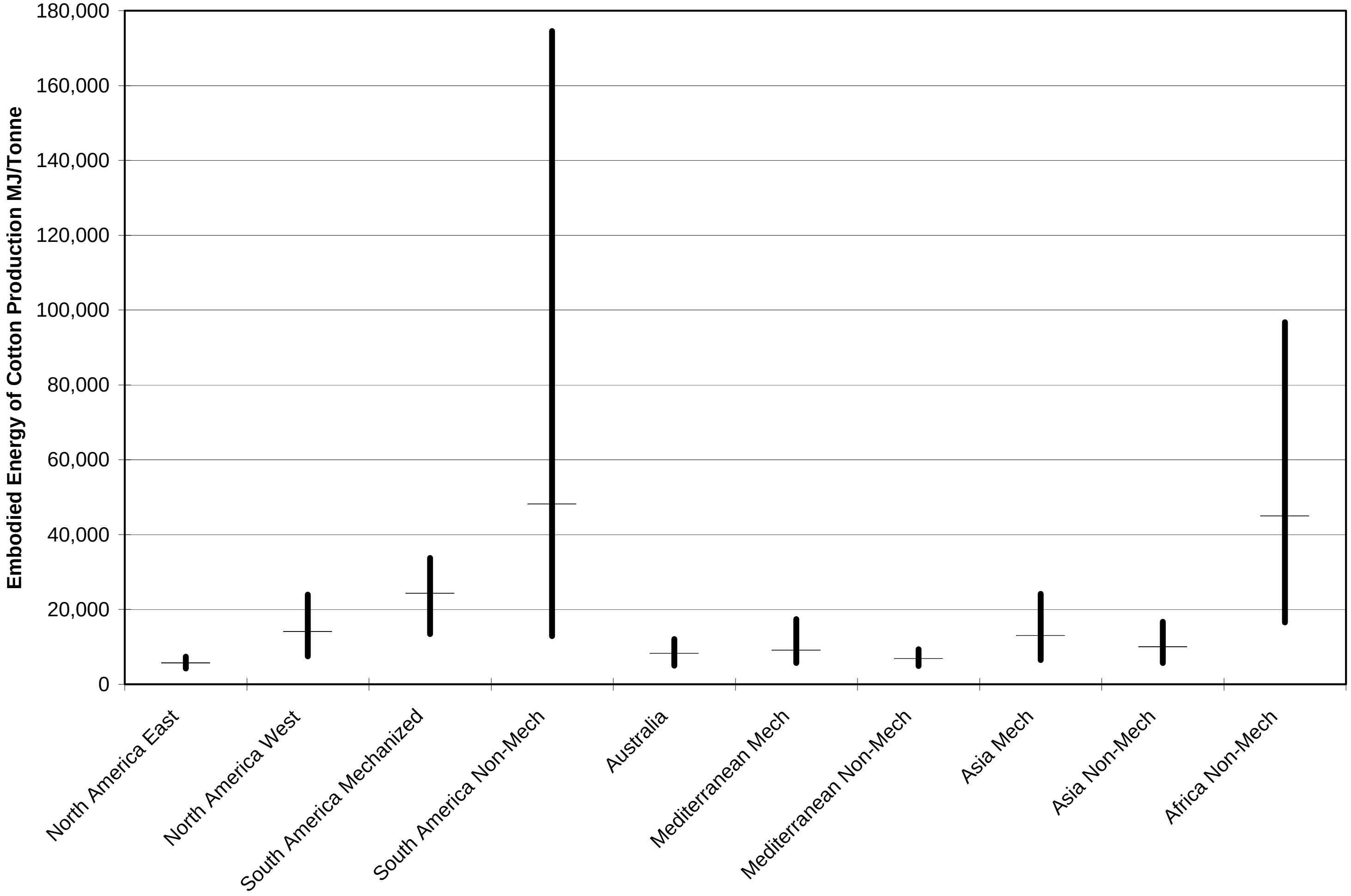


Figure 5: Energy of Cotton Production with Manure Energy Costs. Cross-marks represent means, and upper and lower ends of vertical bars represent the upper and lower 90% confidence intervals, respectively.

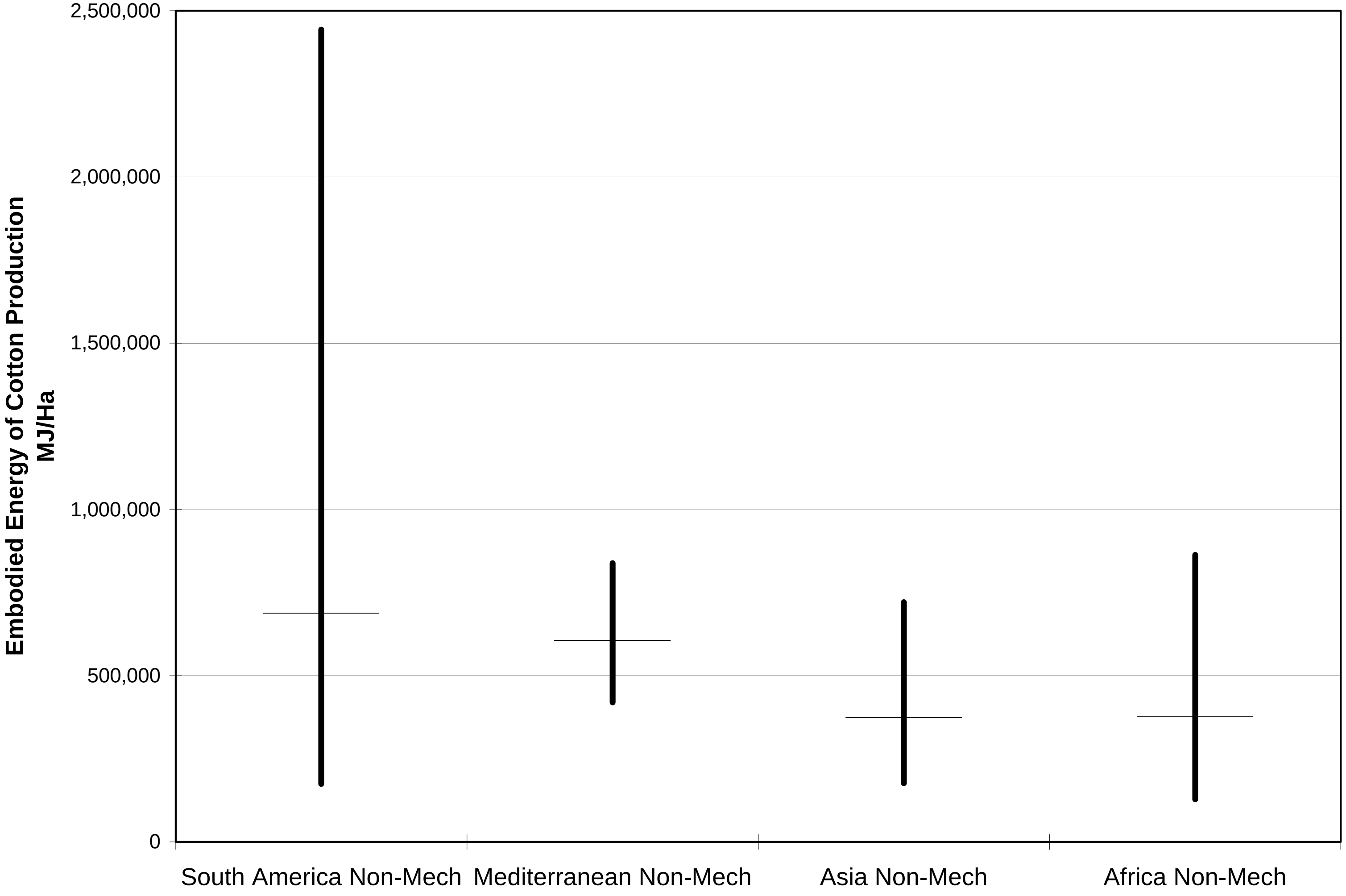


Figure 6: Embodied Energy of Cotton Production (MJ/ha). Cross-marks represent means, and upper and lower ends of vertical bars represent the upper and lower 90% confidence intervals, respectively.

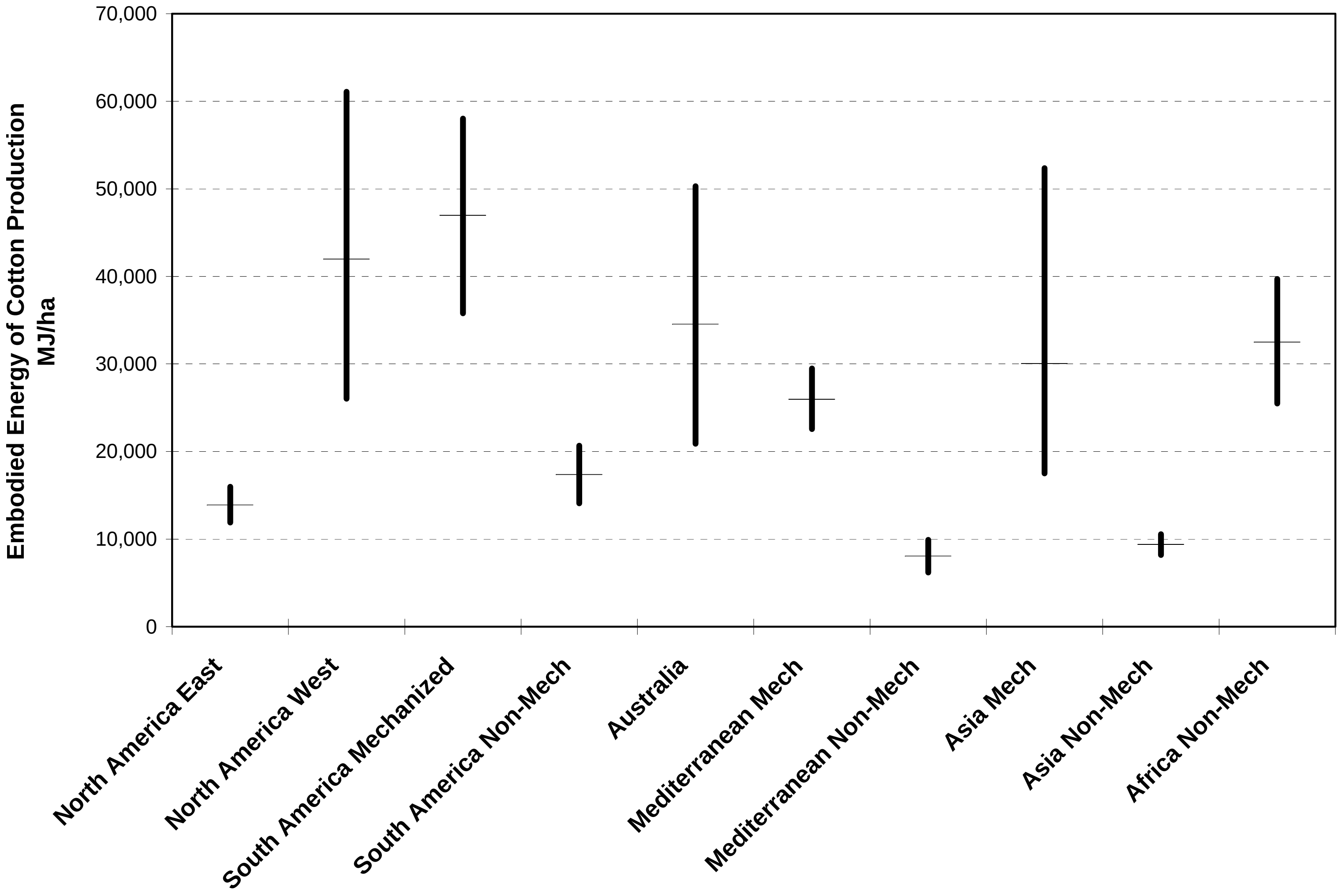
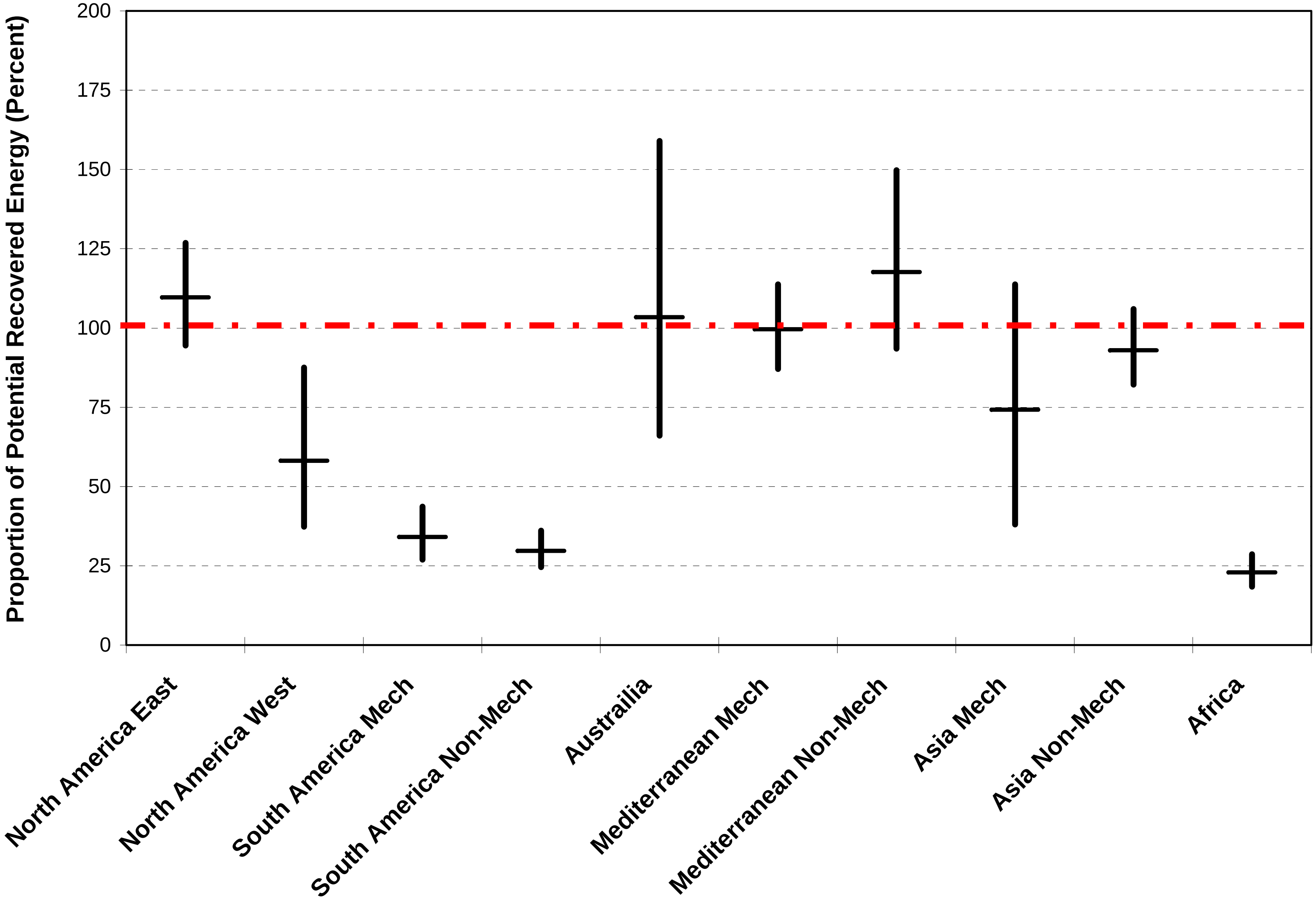


Figure 7: Net Energy of Cotton Production (MJ/tonne). Cross-marks represent means, and upper and lower ends of vertical bars represent the upper and lower 90% confidence intervals, respectively. The red dashed line at 100 percent represents the threshold of net potential energy production.



Interpretation

The energy embedded in a tonne of cotton in the field is dependent upon a variety of factors. In most cases yield was the most sensitive variable impacting embodied energy in a tonne of cotton. Areas with predominantly low yields required more energy per tonne of production than areas with high yields. This held true across agricultural production practices. The most evident approach to reducing embodied energy in cotton, therefore, is to increase yield.

The effect of manure was indicated in this analysis. Use of manure as a green fertilizer has advantages, especially in marginal and low-tech production systems, where capital availability limits access to inorganic fertilizers. However, the opportunity cost in using manure as a fertilizer must be considered; it may not be an energy efficient production strategy if practical ways to utilize manure as a fuel are available to the farmer.

Cotton production yields a high dividend in energy as cottonseed oil and meal. The assessment that six of the ten regional production scenarios could be at least energy neutral is conservative, since many other energy-yielding by-products were not considered. The most sensitive variables for net energy production of cotton were yield, seed yield, and irrigation. Increasing yield and decreasing irrigation demands could dramatically enhance the energy efficiency of cotton production.

This LCA was focused on energy, not green house gasses. These analyses should not be construed as a validation of any production strategy, but rather as a mechanism to assess cotton production strategies with the intent of improving knowledge and efficiency. These analyses are limited by availability of region- and practice-specific data. As more data are collected, the resolution and robustness of this LCA can be enhanced.

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