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Analysis

Trophically balanced sustainable agriculture

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ABSTRACT

Considering an economy without fossil fuels, literally built from the ground, then up, we developed several interactive research models of biointensive farms that use no fossil fuels. Quantifying and summarizing total human labor–energy input and total caloric energy output, we demonstrate that a successfully designed farm can produce a positive energy-return-on-investment (EROI) leaving excess caloric energy available for building economic-community structures (e.g., schools and hospitals). Farm products with negative EROI must be coupled with other products with positive EROI to assure nutritionally balanced diets are maintained while still achieving an overall positive EROI for the total agroecological operation. We show that similar to the ecosystem, energy budgets are tight which makes for difficult decisions on diet, farm plot diversity, and energy profitability for future growth. Considering the totality of this low energy agro-system based economy, we simplify many operational variables into a unique graphical solution space, which reveals both reasonable expectations of agroecological EROI performance, and extreme asymptotes, beyond which indicate regions of system failure.

1. Introduction

The inevitable peak production in fossil fuels (Hirsch et al., 2005; Kharecha and Hansen, 2008) coupled with an increasing world population demand (EIA, 2007; USCB, 2008) will result in dramatic changes with regard to anthropocentric energy systems and their respective local and distal supporting ecosystems. Also, reasonable CO_2 emission scenarios (e.g., global temperature rise held to less than 2 °C) will require extreme reductions in fossil fuel usage in the near decades [e.g., 40% reduction from 1990 levels in the next 10 years (Allison et al., 2009) and 80% reduction from 1990 levels in the next 40 years by developed countries (Meinshausen, 2007; Watkins, 2007/2008)]. Newell et al. (2006) summarize the potential and range of effects of various policies introduced to reduce energy consumption and carbon emissions. Yet, accounting for existing and projected new developments in energy efficiency within modern society, the National Academy of Engineering (Lave, 2009) reports that if the U.S. continues with expected technological improvements, it can only reduce approximately 30% of the energy that would have been used by 2030. Maréchal (2010) shows that energy consumption habits contradict rational choice theory "where the current carbon-based Socio-Technical System constrains and shapes consumers' choices through structural forces". Referencing social psychology, Townsend and Bever (2001) succinctly summarize, "most of the time what we do is what we do most of the time" after showing that the pursuit of social and economic stability is what characterizes modern energy consumption trends and associated research.

Countering the ongoing research paradigm of improving current devices, processes, and social efficiencies (e.g., Franzluebbers and Francis, 1995; Hülsbergen et al., 2001; Mrini et al., 2002) to ease the transition from fossil fuels, we specifically consider an agro-economy with no fossil fuels. This perspective forces the associated anthropocentric sub-sector to research, engineer, and operate within a local eco-trophic envelope. More importantly, through this approach, novel insight, perspectives, and ideas not apparent in Maréchal's existing Socio-Technical System and its modern energy models are developed. Moreover, this approach may generate technologies capable of affecting Less Developed Countries (LDCs) in a meaningful way. University of Georgia's (UGAs) Low Energy Systems (LES) modeling program is conducting research to assess the needs of modern population levels with little to no fossil fuels. Here, we present models of non-fossil-fuel vertically integrated agricultural systems where energy (Caloric) outputs are managed to exceed human labor-energy inputs. (We use the standard convention where one food Calorie equals 1000 chemist calories (1 kcal) where the former is usually capitalized and the latter is not.) Ostensibly, excess labor energy or biofuel crops are then available to be redirected from the local agricultural operation to community and economic development. Thus, a local economy can be launched.

As high-density energy supplies dwindle or the negative ramifications of fossil fuel consumption become better understood, plans and corresponding efforts to reduce energy consumption are a looming

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priority in a variety of sectors of the US economy. Representing a large energy consumer in the U.S., the nation's food supply system is at the center of this issue. The current American food supply is driven almost entirely by non-renewable energy sources [consider the often cited trend that U.S. agricultural labor, as a percentage of the economy's total labor, went from 64% in 1850 to 2% by the year 2000 (Smil, 2008)], which permits our modern food production and distribution system, including sustainable agriculture, to use significantly more energy than it produces. Pimentel and Pimentel (1983) established an energy input–output perspective as a measure of agricultural efficiency showing, for example, that fruits and vegetables required two Calories to produce one food Calorie of output and various animal products required 20, even up to 80 Calories of input energy for each food Calorie of output. Although many studies have followed, Gussow (1991) is frequently cited as showing 15 Calories of energy input were used for each Calorie of energy produced in the American food supply system in the 80s. The estimates continue to vary due to varying boundaries, quality of data sets, volume of products produced, etc. To provide a visual perspective to this relationship, Fig. 1 shows Heller and Keoleian (2000) data (because it is reasonably recent) which approximate seven equivalent Calories of energy consumed by the U.S. food system for each agricultural Calorie yielded. These embodied energy inputs continue to be evaluated and debated. For example, packaging has wide variability and is often estimated as requiring much higher energy inputs (Pimentel et al., 2008; Pimentel and Pimentel, 2008) which is one research area that may explain Heller and Keoleian's lower ratio than past estimates of the energy returned on energy invested (EROI) for the U.S. food system. Despite variations in estimates, the summary conclusion as depicted in Fig. 1 is that the EROI in agriculture is not considered sustainable when compared to self-organizing ecosystems.

Although a wide range of public and private resources are developing to both understand and reduce nonrenewable energy consumption (examples include: DOE's Energy Efficiency and Renewable Energy Program and their Alternative Fuels Program, the Bioenergy Feedstock Information Network (BFIN), and the university-based Sun Grant Initiative, etc.), the initiation of energy studies specifically for agriculture has been considerably smaller, and noticeably more limited with regard to sustainable agriculture. Biofuels are one exception and an area of intense research (DOE, 2003; EUROPA, 2007; Tilman et al., 2009); however, agriculture intensive energy research is primarily dominated by renewable energy research that is secondarily applied to agricultural systems. For example, the USDA's Sustainable Agriculture Research and Education (SARE) organization's 2006 workshop was organized to “bring together various groups and agencies that focus on renewable energy and sustainable agriculture to exchange information and identify areas of commonality”. Yet, the concluding summary of potential topics for research almost exclusively referenced plant-based fuel areas (a.k.a., biofuels) to aid farm operations or simply for farm production and sale. The summary did identify, however, that an increase in energy conservation needs to be added to future discussions. A comprehensive systems approach with a long-term sustained effort towards the understanding of energy in agriculture is needed where organic farming currently recognizes the use of mechanical cultivation and in general embraces energy conservation only indirectly by promoting the reduction of climate change practices (for example, The Rodale Institute). No policies, goals, or plans are in place to address renewable or nonrenewable energy in sustainable agriculture. As such, we jump ahead of the current issue and consider organic operations without fossil fuels to begin engineering the foundation for future considerations and to identify technology and insight that can potentially be inserted into today's modern or less developed societies.

First, we discuss the sustainable farming method used in the modeling effort (GROW BIOINTENSIVE®) primarily because it has a dataset of product yields available in the literature and, due to its mature stage of development, it minimizes the variability of several input values for our theoretical model. We address how vitamin B_{12}, of particular concern in plant-based diets, is accommodated for this sustainable farm model simulation. We then articulate the software and computational aspects of the model inputs, outputs, and how these are coupled. Several scenario farms representing different inputs and outputs are generated, presented, and discussed. We conclude with a discussion of the ramifications of an energetically balanced sustainable agriculture system.

2. Materials and Methods

For development and corresponding assumptions, the theoretical model is assumed to be a biodynamic French intensive style farm located in the Piedmont Ecoregion of Georgia, USA. The Georgia Piedmont is a geographically contiguous area in the upper half of the state situated between the Coastal Plain of central to south Georgia and the Blue Ridge Ecoregion to the north. The Piedmont is characterized by mineral and rock deposits and readily apparent red iron oxide laden soils. Biodynamic French intensive farming, developed extensively over most of the 20th Century, is an advanced ecologic farming system that emphasizes food quality and soil health. Rudolf Steiner initiated biodynamic agriculture over a series of 8 lectures in 1924 (Steiner, 1993) as a direct response to the increased use of

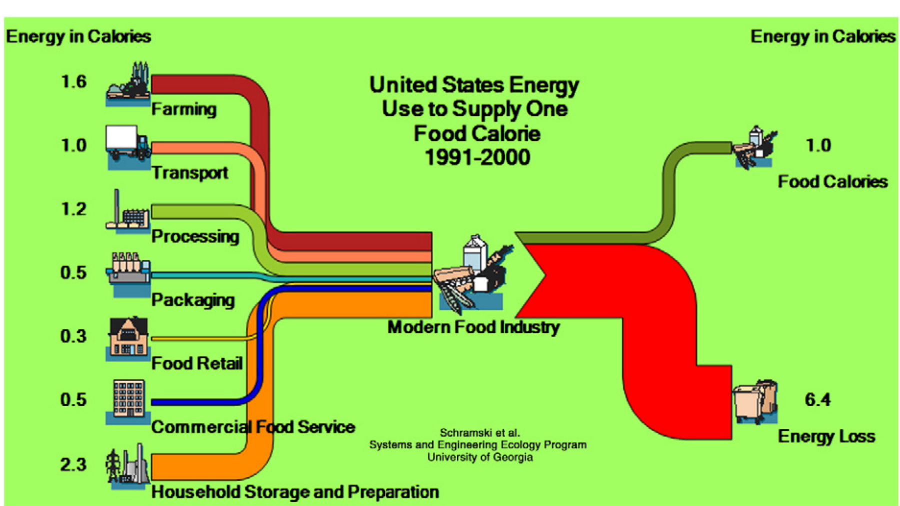

Fig. 1. Adapted from Heller and Keoleian (2000).

chemical fertilizers and their depletion of soil structure and food quality. The French intensive method, developed outside Paris through the early- to mid-1900s to offset decreasing land availability, promoted keeping plants very close together to reduce weed growth, maintain moisture levels, and ultimately create microclimates that proved to encourage extremely high production (Gliessman, 1990). Alan Chadwick (2008) combined these approaches throughout the 1900s into Biodynamic French Intensive farming ultimately creating a stable, repeatable, and documented high production, organic farming method. John Jeavons (2001a,b,c,d,e, 2006) is credited with further development and documentation of this methodology over the last 40 years into the sustainable mini-farming practice of GROW BIOINTENSIVE® (GB). Other organic farming techniques are similar and with some effort, could be substituted in this modeling effort. To minimize pests (e.g., weeds, insects) and improve sustainability (e.g., promote genetic diversity, use little to no fertilizers) the varying methods generally focus on both soil and plant development with continuous knowledge enhancement applied to specific (local) conditions. Given the immense biological complexity associated with geographic diversity, organic methods respect and promote the deep understanding and knowledge development necessary for local community based efforts.

We use GB farming for our model development for these reasons and because their harvested yields are documented in the literature and thus provide a sufficient dataset to initiate our computational model development. Like all organic farming techniques, GB farming is a comprehensive process that is participant and site dependent. Program implementation and farmer's skill development take five to ten years. Soil construction, product diversity selection based on location, seed cultivation, etc. all require ongoing maintenance and generate a substantial year-to-year learning curve. We assume the start-up/learning period is successfully completed and use Jeavons' steady-state plot sizes, inputs, and outputs for an average GB mini-farm operation. Developing a sustainable operation within its own boundaries (closed system soil humus sustainability) through balancing nutrient gains (rainfall, composting, etc.) and losses (runoff, leaching, harvesting, etc.) is extremely complex and beyond the scope of this paper.

In general, according to GB research, a sustainable operation including the perpetual maintenance of supporting soils, can be developed and eventually fine-tuned to a reasonable level of consistency if the overall mini-farm maintains an approximate 60% grain-seed, 30% root, and 10% vegetable garden plot distribution ratio (a.k.a., 60/30/10). Duhon (1985) defines weight-efficient crops as requiring nine pounds or less to meet daily Caloric requirements and area-efficient crops requiring 16 beds or less at medium-yield harvests to meet an annual Caloric requirement. The grain-seed crops (carbon-and-Calorie crops) generate large amounts of carbon for compost and high Calorie foods and are weight-efficient. The root crops produce high Calorie foods and can be area- or weight-efficient. The vegetables are low Calorie, low carbon, and produce vitamins and minerals as needed to complete a sufficient diet. In the GB system, one bed is 100 ft^2. Annually, one person can sufficiently farm the 40 beds (4000 ft^2) of growing area required to implement the 60/30/10 system. This is roughly 5000 ft^2 including paths.

Vitamin B_{12} is not available in a purely plant based diet. A large structurally complicated vitamin, only a bacterial fermentation process artificially produces it. Reasonably assuming this process is not available for a small farm operation, an animal product needed to be added to the theoretical GB farm operation algorithm to assure a nutritionally balanced output. Any one of a large number of animal product combinations can achieve the necessary quantity of B_{12} (the inclusion of this potential variety is beyond the scope of this intended research). For simplicity and as a placeholder for future research, we used chicken eggs. Chickens are omnivores eating plant matter and bugs. They are separated from the gardening plot during the growing season but are normally allowed to eat post harvest farm plot detritus and are a known source of high nitrogen fertilizer during this process. Multiple methods house chickens with most farmers providing some form of day and night protection from raptors and nocturnal predators. For sustainable farms, often portable pens or "tractors" contain the chickens within several dispersed areas. These tractors are shifted around the property to prevent denuding. Multiple studies of free-range indigenous chickens, unsubsidized in their diet, in underdeveloped countries, demonstrate they will produce at least 50 eggs/hen/year with moderately increased production achieved with the addition of general household wastes or cheap non-conventional feed resources such as bran (Alemu, 1987; Alemu and Tadelle, 1997; Fisseha et al., 2010; Solomon, 2004; Tadelle et al., 2000; Tadelle and Ogle, 2001). For our model, we reasonably assume 50 eggs/hen/year to satisfy our B_{12} supplement. However, all nutrients and Calories associated with these eggs are added to the overall results.

An interactive computational model (Microsoft Excel with supporting Visual Basic programming) was developed which, when a user provides specific crops and quantity of plots as inputs, the software then supplies a comprehensive list of energy (Calories) and nutritional outputs (vitamins and minerals) (Jeavons, 2006; USDA, 2009). Table 1 lists a Georgia Piedmont mix of grain, root, and vegetable farm products selected from the dataset of Jeavons (2006) that are included in the interactive model as potential user selected crop choices. As noted earlier, this project deals exclusively with food Calorie dimensional units, which are commonly capitalized to denote their difference from chemist calories where 1 Cal = 1000 cal.

The theoretical 4000 ft^2 farm model is numerically divided into 40 beds each 100 ft^2 such that the grain, root, and vegetable crops are divided into 24, 12, and 4 possible beds respectively to meet the 60/30/10 GB division goal for reasonable soil quality and long-term production sustainability. The model algorithm allows a user- initiated interactive selection from the lists of grain, root, and vegetable crops with the forced constraint that the final number of beds in each

Table 1
Medium- and high-yield harvests in Calories/bed/day (Jeavons, 2006).

Grain & Seed			Root			Vegetable		
	Medium	High		Medium	High		Medium	High
Wheat	41	99	Potatoes	191	746	Peanuts	70	169
Cereal rye	42	100	Garlic	222	444	Soybeans	41	72
Oats	34	63	Jerusalem artichoke	195	435	Kidney beans	41	99
Barley	43	104	Leeks	364	729	Burdock	134	269
Corn	77	104	Parsnips	222	446	Cassava	119	239
Sorghum	67	101	Sweet potatoes	180	539	Onions	94	254
Filberts	118	236	Salsify	204	408	Turnips	68	123
Amaranth	76	152				Rutabaga	179	357
Quinoa	57	114				Tomatoes	50	109
Fava beans	13	25						
Sunflower Seeds	35	71						

category shall meet the 24/12/4 division requirement. The model also allows a quantity selection of egg-laying hens to supplant the B_{12} vitamin deficiency of a plant only diet. For simplicity, we assume 65 laying hens for the medium-yield and 150 laying hens for the high-yield harvest operations. These quantities are chosen to keep B_{12} from becoming a deficient nutrient in any of the presented scenarios. Given the complexity associated with animal operations, a sufficiently diverse and efficient husbandry operation to supply B_{12} is left for a different study. Accessing the USDA nutritional capacity and Jeavons' Caloric output for each farm product, the model calculates the combined nutritional quality and Caloric output of the overall selection. The modeler interactively adjusts selections until a balanced nutritional diet is achieved coupled with the requisite 24/12/4 farm plot division.

Table 2 shows several successful whole system farm selections where successful is defined as meeting or exceeding the USDA's daily nutritional and energy requirements for a balanced diet. For example, considering the potential crop selections presented in Table 1, for Farm 1 we selected the individual crops from the choices available until our model output showed we exceeded a nutritionally balanced diet while maintaining the required 24/12/4 plot division requirement. For this farm selection, we show both the medium- and high-yield harvest outputs. The total energy output for medium-yield operation is 5409 Cal/day. Although this was a successful whole system farm selection (provides equal to or greater than a 100% nutritionally balanced diet), the software's generated output shows the limiting essential (vitamin, mineral, or energy) to be sodium (Na) where 165% of the USDA's required daily sodium intake is produced. Therefore, sodium is the limiting essential and the farm plot (including eggs produced from 65 hens) could not support more than 1.65 people (i.e., all other vitamins, minerals, and Calories are output in quantities greater than 165% of the recommended daily requirement). Shannon's Diversity and Equitability Indexes for the farm plots are 2.62 and 0.93 respectively (Krebs, 1989; Shannon, 1948). Shannon's Index accounts for both abundance and evenness of the species present. For ecosystems, typical index values range from approximately 1.5 (low species richness and evenness) to approximately 3.5 (high species richness and evenness). Similar to ecosystem performance, it is proposed here that for a sustainable farming operation, higher Shannon Index crop selections are preferred to increase multi-dimensional defenses and minimize susceptibility to disease and infestations. The Equitability Index provides a means to consider species evenness and assumes a value between zero and one with

Table 2
Daily Caloric outputs for various farm product selections.

	Farm 1			Farm 2		Farm 3		Farm 4		Farm 5		Farm 6		Farm 7	
	Beds	MY* Cal	HY* Cal	Beds	Cal	Beds	Cal	Beds	Cal	Beds	Cal	Beds	Cal	Beds	Cal
Grain/seed															
Filberts	4	472	946	24	5673	24	5673	24	5673	24	5673	10	2364	11.6	2742
Wheat	3	123	296									2	197	0.7	69
Cereal rye	2	84	200									2	200	0.8	80
Oats	3	102	188									2	126	1	63
Corn	8	616	835									4	417	1.1	115
Barley	2	86	208									2	208	0.8	83
Sorghum	2	134	202									2	202	0.9	91
Amaranth														1.8	273
Quinoa														1.4	160
Fava Beans														0.5	13
Sunflowers														3.4	241
Root															
Potatoes	1	191	746	12	8950			2.55	1902	0.58	431	1	746	0.6	447
J. artichoke	4	780	1739			3.9	1697	7.84	3409	8.72	3791	5	2174	6.7	2913
Leeks	2	728	1457			8.1	5899	1.05	765	1.43	1042	2	1457	2.2	1603
Salsify	2	408	815					0.56	228	1.27	519	2	815	0.6	245
Garlic	1	222	444											0.4	178
Sw. potatoes	1	180	539									1	539	1.1	593
Parsnips	1	222	446									1	446	0.4	178
Vegetable															
Rutabaga	2	358	715	4	1429	4	1429	3	1072	2.5	893	2	715	0.6	214
Kidney beans								1	99	1.5	149			0.6	60
Soybeans	1	41	72									0.5	36	0.4	29
Peanuts	1	70	169									1	169	0.4	68
Turnips												0.5	62	0.4	49
Burdock														0.4	108
Cassava														0.4	95
Onions														0.4	102
Tomatoes														0.4	44
Hens															
Quantity		65	150	150		150		150		150		150		150	
Calories		592	1479		1479		1479		1479		1479		1479		1479

Totals	Farm 1		Farm 2	Farm 3	Farm 4	Farm 5	Farm 6	Farm 7
	1-MY*	1-HY*						
Beds	40	40	40	40	40	40	40	40
Plant Cal.	4,817	10,017	16,052	14,698	13,148	12,498	10,873	10,856
Total Cal.	5,409	11,496	17,531	16,177	14,627	13,977	12,352	12,335
Limiting essential	Na	Na	Vitamin A	Na	Na, Riboflavin	Energy, Na, Riboflavin	Na	Na, Riboflavin
People supported	1.65	3.72	1.26	4.25	5.25	5.59	4.24	4.85
Shannon's Diversity	2.62	2.62	0.90	1.09	1.24	1.22	2.51	2.61
Shannon's Equitability	0.93	0.93	0.82	0.78	0.64	0.63	0.89	0.79

*MY is a medium-yield harvest, HY is a high-yield harvest, Farms 2 thru 7 use high-yield harvests.

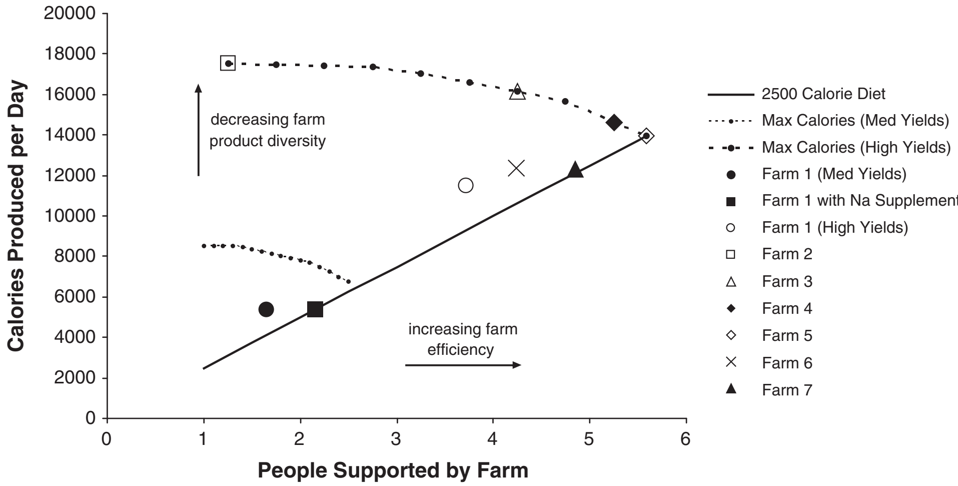

Fig. 2. Theoretically possible Caloric energy outputs of a 4000 ft^2 fossil-fuel-free Grow Biointensive® 60/30/10 farm supplemented with egg laying hens located in the Georgia Piedmont, USA manually farmed by one individual. All farms shown have 40 beds and provide 100% or more of the U.S.D.A. recommended vitamins and minerals.

one representing complete evenness. The software also computes the farm's total Caloric output and then compares it to a generally accepted per capita Caloric input for sustainable health. Daily per capita energy input requirements vary considerably with age, weight, physical conditioning, gender, etc. (Babatunde et al., 2010; FAO/WHO/UNU, 2001; Leslie et al., 1984; WHO, 1985). As a consistent assumption, we use the commonly referenced WHO published average of 2500 Calories per day to sustain each person (FAO/WHO/UNU, 2001; WHO, 1985).

To understand the interactive capabilities of the model's input and the corresponding output, consider the medium-yield sodium-limited Farm 1 shown as a solid circle data marker in Fig. 2. If sufficient sodium supplement were artificially added, energy output from the selected crops becomes the limiting essential. The modified medium-yield Farm 1 then supports 2.20 people as indicated by the solid square data marker. In other words, although this farm provides greater than 220% of the remaining USDA's recommended vitamin and mineral quantities (except sodium which was artificially augmented), this farm produces exactly 220% of the WHO recommended per capita energy intake of 2500 Calories per person. Thus, a medium-yield Farm 1, sufficiently supplemented with sodium, could support 2.2 individuals. As shown in Table 2 and with the open circle data marker in Fig. 2, if high-yield outputs from Table 1 are substituted for the same Farm 1 configuration with no external sodium supplements, the total energy output rises to 11,496 Cal with sodium remaining the limiting commodity (thus 3.72 individuals supported). By varying the software inputs (varying farm products depicted in Table 1 or bed quantities), similar to the example expressed in the Farm 1 selection, the software generates infinitely diverse combinations of practical system solutions for the 4000 ft^2 farm operation.

3. Results

Considering the infinite range of farm system solutions as they pertain to varying inputs and subsequent outputs, we specifically explore limiting factors to improve our understanding of sustainable agriculture's capacity and limitations, particularly as to how system responses affect the farm's combined energy output. The objective is to identify and quantify respective boundary limits with respect to, for example, harvest diversity, total energy output, and farm efficiency. Farm efficiency is defined here as the number of individuals supported by the farm (accounting for total energy, vitamin, and mineral outputs) per Jeavons' assumed input of a single farmer's manual labor to the 4000 ft^2 GB operation [where farm efficiency = (total people supported by 4000 ft^2 farm)/(one farmer working 4000 ft^2 farm)].

Fig. 2 depicts a potential solution space for all complete diet combinations of the Table 1 farm product choices (e.g., wheat, barley, oats) and their quantities (number of beds and their subsequent yields). In other words, only nutritionally acceptable, 100% or greater of all USDA recommended supply of vitamins and minerals are plotted. Also, as a relative boundary, the solid ascending-positive sloped line represents the FAO minimum 2500 Calorie diet per individual supported by the farm output (FAO/WHO/UNU, 2001). Assuming all farms plotted on this graph supply a complete nutritional diet, energy output-limited farms operate below-right of this line, and energy output-sufficient farms, operate above-left of this line. Theoretically, no energy sustainable farm should operate below-right of this line, e.g., if the intent is to support two individuals with this farm, then the output should not be below 5000 Calories.

Two maximum energy output lines (we call them boundaries) for the 40-bed operation are indicated (Fig. 2) using the planting options available in Table 1. The lower and upper (dotted and dashed) maximum Calorie lines represent medium- and high-yield harvest operations whose product mixes were computationally optimized to maximize Caloric output. Each of these farms supplies 100% or more of the USDA's nutritional requirements with total energy output maximized at each requisite farm efficiency (horizontal axis). In total, ten farms were modeled to construct the high-yield maximum energy output and 16 farms were modeled to construct the medium-yield maximum energy output trend lines shown where the optimization/computational methodology used to generate these data points is discussed later. Sustainable agriculture is an extensive learning and developmental process for each piece of land cultivated where different harvest yield rates are the direct result of different knowledge and experience levels. For example, Jeavons refers to beginning, intermediate, and fully experienced food growers in the GB method where a fully experienced food grower (high-yield harvests) has over 10 years farming experience, usually situated in the same soil. Soil quality, soil capability, and various plant diversity schemes to maximize harvest yields and seed production while minimizing disease, harmful insects, and weeds are only some of the important aspects of food production to be meticulously engineered over sequential seasons. Medium-yield harvests represent the intermediate stage for a farm and farmer, short of the fully experienced stage of development. The gap between the medium- and high-yield maximized energy output lines (dotted and dashed lines) in the solution space of Fig. 2 represents the importance of farmer skills, soils development, and a total system approach, with regard to annual sustainable farm efficiency. The location of the high-yield maximized energy output line (dashed line) also represents a boundary or asymptote of maximum energy output for the 4000 ft^2 growing space.

Microsoft Solver (MS) [which uses the Generalized Reduced Gradient (GRG2) nonlinear optimization code (Lasdon et al., 1978; Lasdon and Smith, 1992)] was used to optimize (in this case, maximize) the farm energy output for medium- and high-yield harvest configurations. These are shown with the lower dotted line (medium-yield harvest outputs) and upper dashed line (high-yield harvest outputs) as functions of farm efficiency in Fig. 2. The MS algorithm was forced to maintain a 100% or greater USDA recommended level of vitamin and minerals with all generated farm configurations. Within this overriding constraint, the MS optimization routine then maximized farm energy output by varying and ultimately optimizing both the Table 1 farm product selections and their bed quantities while strictly maintaining both the GB 24/12/4 farm plot division and the 40 bed total requirements. Farm 2, shown in Table 2 and Fig. 2, represents the maximum energy output possible at 17,531 Cal for the farm products listed in Table 1 organized in the 24/12/4 configuration requiring 40 beds total and will support 1.26 people with vitamin A being the limiting essential. This is the least diverse farm configuration (Shannon Index = 0.9) requiring only 3 crops (filberts, potatoes, and rutabagas), the maximum number of beds (24, 12, and 4), and the maximum egg-laying hens (150) to meet USDA nutritional requirements. Farm configurations, which continue to maximize Caloric output but support fewer people (lower farm efficiency than 1.26 people), would be possible but would simply require less than 40 beds. Therefore, Farm 2 represents the optimum configuration of Table 1 farm products to supply the highest Caloric output with 100% or more of the USDA required minerals and nutrients, a 24/12/4 GB plot configuration, and 40 beds total. Although Farm 2 does not represent a reasonable diet, it does represent a system limit.

The maximizing numerical algorithm was used to define the food system's maximum energy production capabilities as a function of the number of people supported by the farm (farm efficiency). Farms 3, 4, and 5 in Table 2 and shown in Fig. 2 are three exemplars of the nine additional high-yield harvest farms used to delineate the farm's maximum energy output. As the number of people supported by the farm was increased, the software forced an increase in the farm product diversity to support the higher nutrient and mineral requirements for more individuals. Thus the total Caloric output is reduced to accommodate the higher plant diversity causing the maximum energy output line to decrease with an increase in the number of individuals supported. In Farm 3, the optimization algorithm replaced potatoes with artichokes and leeks, subsequently increasing the number of individuals supported to 4.25 (sodium becomes the limiting essential) with a total farm energy output of 16,177 Calories. Farm 4's optimization adds salsify, potatoes, and kidney beans to the overall diversity, again increasing the number of individuals supported to 5.25 (now, sodium and riboflavin are limiting essentials) reducing the total energy output to 14,624 Calories. Similarly for Farm 5, the algorithm changed the overall quantities of products in Farm 4's configuration to increase the number of people supported to 5.58 with a total energy output reduced to 13,939 Calories. Farm 5's energy output intersects with the FAO 2500 Calorie Diet line, as shown in Fig. 2, and the limiting commodities are sodium, riboflavin, and energy. Thus, the high-yield harvest's energy line and the FAO 2500 Calorie Diet line are upper and lower boundaries, respectively, to the farm's solution space converging in the range of the Farm 5 commodity and quantity choices and representing a potential optimum point. As quantified with the Shannon diversity index, the farm species overall diversity continually increases from Farm 2 to Farm 5. This increase in diversity accommodated the nutritional requirements of the corresponding increases in the number of people supported by the farm while sacrificing the overall maximum energy output of the system.

Although the boundaries to the farm solution space are revealing, boundary farm operations are not reasonable and provide no room for unpredictable events, uncertainties, or errors. The high-yield harvest Farm 1 is one example of a reasonable selection within the solution space offering a USDA and energy sufficient diet with some diversity in product selection potentially supporting 3.72 people. As a test to improve farm efficiency, Farm 6 was generated by slightly adjusting both the product selection and bed quantities from Farm 1 thus improving farm efficiency to 4.24 and only decreasing diversity from 2.62 to 2.51. This may represent the type of useful adjustment within the solution space to improve the optimization of a targeted parameter. As another example, Farm 7 is a forced diversity of at least 40 ft^2 (bed size = 0.4) of all potential Table 1 farm products. This adjustment decreases the overall energy output ever so slightly from Farm 6 (12,353 Cal down to 12,335 Cal) but also increases the farm efficiency from 4.24 to 4.85 people supported while also increasing overall diversity to 2.61.

4. Discussion

As natural resources continue to be depleted locally, sustainable agricultural systems will eventually move towards material- and energy-neutral balances with regard to their adjacent ecosystems (e.g., carbon, nitrogen, water, biota, energy, etc.). The luxury of distal supplies or deposits to accommodate unbalanced local environmental relationships is diminishing. System approaches such as low-input agriculture (House and Brust, 1989; Pimentel et al., 1989) or traditional ecological knowledge (TEK) approaches (Martin et al., 2010; Stinner et al., 1989) will become mainstream practices rather than soft science concepts pursued only by a few. They will comprise the systems tools to comprehensively support a better understood input–output, balanced relationship with local environments to sustain a large-scale food supply network that may be much less centralized. One challenge attributed to this era of agroecology (Gliessman, 1990, 2006; Jackson, 1980) will be to determine the boundaries of these input–output calculations such that future communities will reconnect with their local habitat in ways not currently envisioned. Essentially, a systems oriented ecologically balanced agriculture is inevitable (Francis and Madden, 1993), although the timeline of implementation is unknown.

Predicting the staged implementation of a systems approach to the current agricultural endeavor and then selectively inserting effective, ongoing engineering research, is difficult at best. This model precludes this quandary by addressing an agroecological economy of energy as initiated from one person's harvest with no external energy or material supplies. If the labor of one farmer on an ecologically balanced farm operation can generate sufficient energy, nutrients, and diet diversity to support the existence of more than one individual, then theoretically at some greater scale, the excess labor (or bioenergy cropping if this were pursued) is available to build and operate a community and associated economy (e.g., businesses, schools, etc.). A core building block for a community's relationship with its local environment emerges forcing its anthropocentric sub-sector to operate within its local ecosystem's energetic (eco-trophic) envelope.

Many generalizing assumptions are used to construct the energy model results depicted in Fig. 2. We assumed the following:

1. One farmer, on average, can sufficiently manage a 4000 ft^2 food plot annually. This established the denominator of one farmer in the farm efficiency calculations (total individuals supported by food plot/per farmer of 4000 ft^2).
2. Each individual supported by the farm, on average, will require 2500 Calories per day. This generated the per capita Calorie diet line, which represented the lower boundary of the solution space.
3. Jeavons' high-yield output results for his documented GB farm represented the maximum yields for each farm product in the

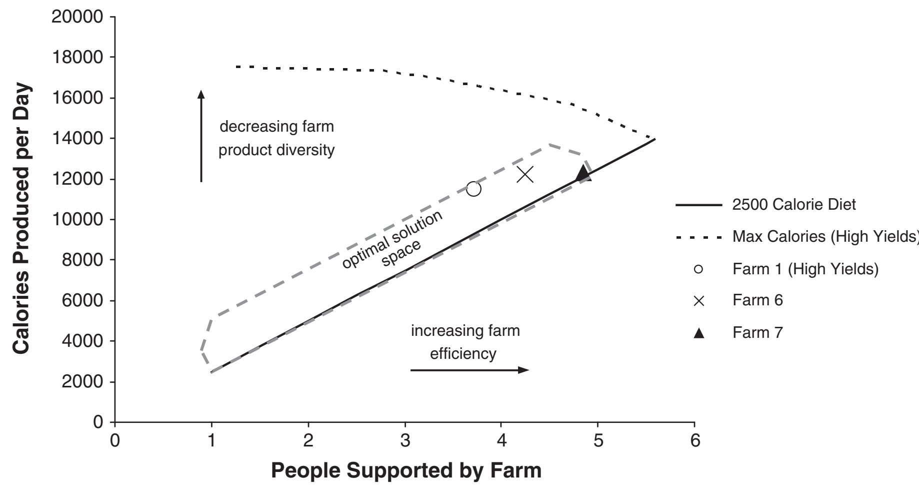

Fig. 3. Optimal solution space to balance farm plot diversity, diet balance, energy sustainability, and farm efficiency for a 4000 ft^2 40 bed, fossil-fuel-free Grow Biointensive® 60/30/10 farm supplemented with egg laying hens located in the Georgia Piedmont, USA manually farmed by one individual.

food plot. This established the high-yield harvest maximum energy output line (dashed line in Fig. 2).

4. Potential Georgia Piedmont farm products were chosen from Jeavons' documented GB farm data. These choices established the variety of output available for the potential farm configurations and thus total diversity considerations.
5. Chicken and egg production was generalized to 150 and 65 egg-laying hens. This satisfied the B_{12} vitamin requirements without dominating the overall diet consumed.

These assumptions and those associated with the dataset ultimately were used to generate Fig. 2 where a degree of uncertainty is always inherent with ecosystem calculations, particularly energy calculations. Nevertheless, the solution space generated in Fig. 2 represents a foundation for future work. Fig. 3 highlights a reasonable target region for a community to consider to balance harvest diversity, a USDA balanced diet, energy sustainability, and overall farm efficiency.

If we consider Georgia, USA, the current energy relationship with the ecosystem can be represented by Fig. 4 where the anthroposphere is a component of the biosphere but not necessarily connected to the local ecosystem.

The food and agricultural sector, at the bottom of the inverted pyramid, represents the lowest energy flow demanded by the anthroposphere. In fact, despite the food and agricultural sector's low ranking in this representation, considering in the most general sense the information depicted in Fig. 1, the energy flow into this sector represents approximately 7 times more energy than the food Caloric energy actually harvested (needed output). When compared to the trophic energy exchanges of the ecosystem, the anthroposphere's use of energy is extreme. Considering our approach, if we remove fossil and nuclear fuels from the potential solution scheme, Fig. 4 is transformed to Fig. 5 wherein the anthroposphere is forced to operate within the local ecosystem's energetic capabilities.

The results demonstrated in Fig. 2 with farm efficiencies greater than 1 then become the economic engine in an agroecological economy of Fig. 5. Consider that the potential for economic improvement may be far greater for LDCs while also providing a means for them to simultaneously address such complex issues as malnutrition and environmental degradation, to name only a few. As the technologies associated with farm efficiency are improved, more individuals are supported by the agricultural operation to make their labor energies available for the social and economic organization and structure. Admittedly by today's standards, these energy margins are extremely small. Yet, if we consider the ecosystem example, a specific species' trophic survival depends on successfully finding a niche of continuous energy potential that neither exploits nor extinguishes its local habitat's ability to perpetually maintain that potential. The anthropocentric endeavor will be no different in this fundamental pursuit, but will, however, be exceedingly different in the level of knowledge

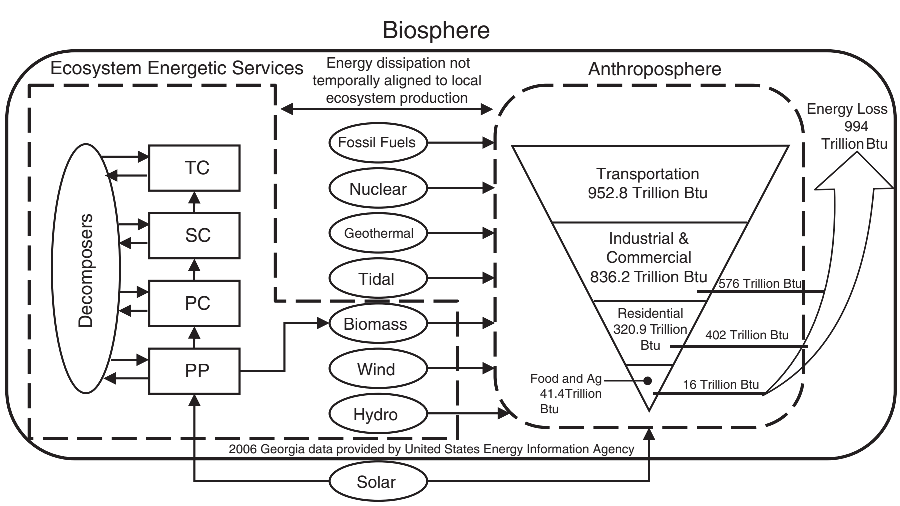

Fig. 4. 2006 energy flow by economic sector, Georgia, U.S.A.

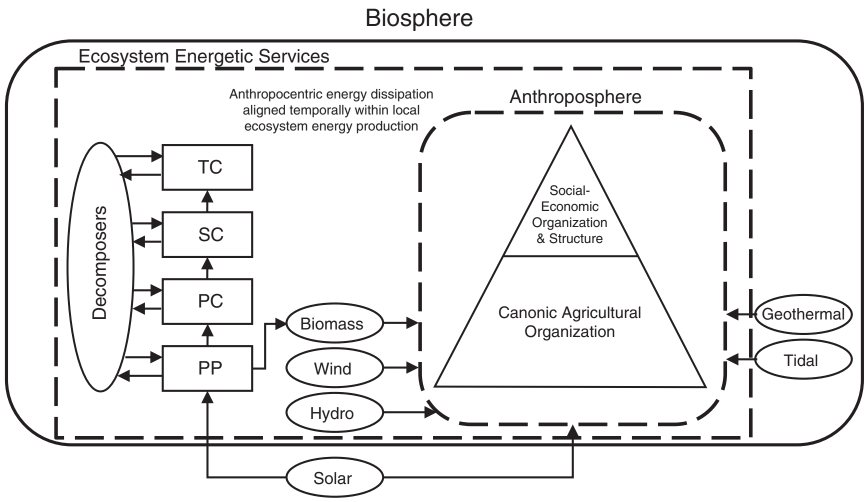

Fig. 5. Temporally relevant (without nuclear or fossil fuels) anthropocentric energy sources in the biosphere.

and information available to establish this agroecological system. This type of perspective forces its anthropocentric sub-sector to operate within its eco-trophic envelope and, most importantly, to develop ideas not apparent in existing energy models and that will help manage the current situation as fossil fuel supplies dwindle.

5. Conclusion

Considered in total, local ecosystems generally acquire no energetic benefit from fossil fuels. This model essentially develops an anthropocentric economy similar to the ecosystem that trades in temporally relevant nutrients and energy flows. Quantifying and summarizing the total farm Caloric output for a single farmer input, we demonstrate that a successfully designed farm can produce a positive energy-return-on-investment (EROI) leaving additional Caloric energy to be routed towards labor-energy or, perhaps, bioenergy, for building and operating extra economic-community structures. Farm products with negative EROI are coupled with other products with positive EROI to assure nutritionally balanced diets are maintained while still achieving an overall positive EROI for the total agroecological operation. We show that similar to the ecosystem, energy budgets are tight which makes for difficult decisions on diet, farm plot diversity, and energy profitability for future economic growth. This type of systems approach towards small-scale farming (e.g., simultaneously accounting for nutritional balance, energy balance, labor needs, etc.) could open new avenues of inquiry for modern sustainable/organic farming approaches, especially in the future as the use of fossil fuel energy begins to decrease. More importantly however, the impact could be profound in Less Developed Countries where nutrition, starvation, labor laws, environmental degradation, etc. are often inextricably coupled at a community level. This type of agroecological systems approach (using GB or any other suitable sustainable/organic farming method), used at a family farm or community level agricultural operation, could simultaneously address these complex and profound global issues. Furthermore, these efforts begin to identify sustainable/organic energy balance expectations or areas for additional research, which are fundamental to the development of any future policy, plans, or goals for energy use in these agroecological production systems.

Unlike the preindustrial infrastructures that existed prior to the advent of a fossil-fuel-driven industrial and informational economy, we are now afforded a considerable level of modern technology and scientific innovation (especially concerning the ecosystem) gained during a fossil-fuel-driven era of rapid discovery. Coupled with this expanded knowledge, the perspectives and methods provided in this manuscript provide an opportunity for a new trophically engineered and inserted fossil-fuel-free anthropocentric agroecological niche (optimal solution space of Fig. 3) within the greater ecosystem.

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