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Original Research Article

Evaluating the relationship between natural resource management and agriculture using embodied energy and eco-exergy analyses: A comparative study of nine countries

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A B S T R A C T

By shifting from animate labor to ever-increasing fossil fuel and other supplement energy subsidies, energy use in human food supply systems continues to increase. As agriculture is the fundamental manner in which humans interact with the environment, it is especially important to understand the relationships between humans, energy, and food. Many researchers evaluate the material and energy resources involved in the food production chain. Energy return on energy investment (EROI) analyses have been particularly useful in assessing the quantity of energy dissipated versus the energy eventually acquired, thus helping to evaluate the overall efficiency of human food systems (i.e., energy invested versus dietary Calories harvested). A complimentary measure, eco-exergy, has been used to evaluate the quality of energies dissipated and generated in ecosystems. To deepen our insight into the dynamic between humans and their food system, we combine these two measures for a food production analysis. Focusing on meat production, adjusted EROI and eco-exergy ratios are used to evaluate both the quantity and quality of energy accumulated and dissipated in nine country's agricultural processes. Each country's food production indicators are then compared with more established methods of sustainability measurement including ecological footprint and biocapacity. The results reveal a significant, highly correlated relationship between these food production indicators and each country's ecological footprint (resources being consumed) while also showing no correlation to their respective biocapacity (resources actually available), thus quantifying a food production disconnect from the local ecosystem. Using these new metrics, we evaluate which changes in each country's food system could result in more environmentally balanced practices, and also how these changes can be realized.

1. Introduction

Energy quantifies how far a property (e.g., temperature, pressure, velocity) is from equilibrium. This so called distance from equilibrium (i.e., gradient) is harvested to perform work, subsequently moving the system closer to equilibrium (i.e., reduction in respective temperature, pressure, and/or velocity differentials) as the gradient is irretrievably compromised to produce work energy, which eventually becomes waste heat. The first law of thermodynamics assures that all of the energy in this transaction can be accounted; nothing can magically appear or disappear from the accounting ledger where inputs must equal outputs. The second law of thermodynamics assures that the quality of energy is always degrading, ultimately to low quality thermal heat energy radiating back to the deepest reaches of outer space.

Thus, where the *ability to perform work* is often used as the simplest definition of energy, ultimately this ability requires an out-of-equilibrium system whose resultant energy gradient is harvested to generate the work effort. This is important to the concept of environmental sustainability; as we use energy derived from the environment, the system (i.e., our biosphere) moves closer to our ultimate equilibrium with outer space (e.g., less biomass/chemical energy). If an energy gradient is dissipated and not replenished, the system moves closer to equilibrium and less energy is available for future actions (i.e., burning stored principal, not renewable interest). For example, as we burn fossil fuels or other auxiliary energy stores and the chemical potential is not being replenished, the earth's chemical biosphere moves closer to

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equilibrium with outer space. More importantly for biosphere functionality, if we burn phytomass more quickly than the ecosystem can replenish these chemical energy reserves through photosynthesis, the biosphere moves irrevocably closer to equilibrium and has less of a stored energy gradient to service the systems' secondary consumers or its own functions. To this point, consider that in the last 2000 years mankind has reduced phytomass stores by ~45%, with 11% depleted since 1900 (Smil, 2012).

In an ecosystem absent humans, the plant kingdom transforms solar energy into phytomass with varying efficiencies depending on species, age, location, limiting nutrients, etc. Additionally, to survive or grow, the animal kingdom must expend less energy searching for, hunting, or cultivating their food than they eventually acquire through their efforts. As is the case over the millennia, phytomass and biomass stores ultimately grew and the biosphere increased its distance from equilibrium (i.e., larger renewable gradients available to harvest for work, future growth, and increased opportunity for additional biodiversity) where this distance is maintained with a continuous flow of solar energy input (Schneider and Kay, 1994a,b). This solar energy (i.e., maintenance energy) is ultimately degraded to lower quality thermal energy output that eventually flows back to the equilibrium of deep space (i.e., inputs = outputs, energy quality is always degrading). At some point during the intensification of farming practices in this, the Neolithic period (c. 12,000–7,000 years BP), a community's energy discharge in the form of biomass alteration or degradation for agriculture became greater than the energy recharge in the form of agricultural biomass produced (food) (Boserup, 1976). This trend has been rapidly increasing in the last few centuries with the increased use of fossil fuels to support our activities, resulting in the biosphere continuously moving closer to equilibrium. This is overwhelmingly due to the loss of the highly concentrated chemical energy of fossil fuels through ignition, but more important to ecosystem functionality, it is also due to the continued loss of the biosphere's biomass primarily through deforestation (Smil, 2012).

For energy balance calculations, one of the simplest ways to measure and quantify energy input and output balance is through an energy return on energy investment (EROI) analysis (Pelletier et al., 2011) and (Pimentel, 1984). EROI analyses have been performed on a myriad of processes including fossil fuel extraction, predator–prey relationships, and agriculture (Cao et al., 2010; Schramski et al., 2011; Murphy et al., 2011; Bardi et al., 2011). Stated succinctly, if an animal expends more energy than it acquires, it dies. However, with supplementary energy (e.g., fossil, nuclear, etc.) as a subsidy, if a human-engineered system uses more energy than it acquires (i.e., agriculture when farm energy inputs exceed Caloric yields), then humans survive for the moment but at the expense of the biosphere's stored energy gradient. Comparable to the common method of gauging the efficiency of anthropocentric systems through an economic cost-benefit analysis, an EROI analysis is centered in the biosphere where stored energy is designated as the currency in nature's economy (i.e., its distance from the equilibrium of outer space). The idea of EROI was implicit in the works of Kenneth Boulding and H.T. Odum (Hall and Cleveland, 2005), and this method of analysis has been explicitly employed since the 1970s when Charles Hall coined the phrase (Gupta and Hall, 2011). Given the thermodynamic absolutisms mentioned, this type of energy analysis has proven to be of particular importance for our increasingly intensive food system forced to feed a growing number of people within an ever diminishing available geographic footprint (Pimentel, 1984; Pimentel et al., 2008; Schramski et al., 2013). Thus the goods and services produced by mankind all have an embodied energy value that represents the earth's stored energy subsequently dissipated (i.e., generally fossil fuels, nuclear, biomass, etc.) to create this product or service. In fact, H.T. Odum's (1996) emergy analysis, which further accounts for all solar energy from the millennia ultimately embodied in the earth's stored energy resources would be yet another perspective, but is outside the objectives of this paper.

While EROI measures the quantity of stored energy used, the quality of that energy is also an important consideration. Presumably, as diversity, connectedness, and general system complexity grew with each new species, the biosphere's energy gradient became more stable (i.e., if the energetics of one individual or species is lost to death or extinction, another biological entity can fill its trophic niche, thus preserving energy flow, stability, and maintenance) (Walker, 1992; Frost et al., 1995; Naeem, 1998). Therefore, given the asperity of evolution's pressure on species development, the rigidity of the biosphere's distance from equilibrium possesses something more than biomass chemical energy. Jørgensen et al.'s (1995, 2000, 2010) eco-exergy metric quantifies, in energy terms, this intrinsic biodiversity improvement through a graduated scale attributed to the information embedded in an organisms' amino-acid sequences (Jørgensen, 2008, 2010). Exergy is the total theoretical work potential of energy (i.e., high quality energy). Eco-exergy is a form of exergy that specifically accounts for the different qualities of biomass in a natural system. In this way, the quality of the energy being consumed (i.e. animate labor versus the burning of fossil fuels) can also be included (Jørgensen, 2008). This is why a complementary eco-exergy analysis becomes an essential indicator of sustainability: when society's food supply is considered as a percentage of the earth's distance from equilibrium, and we consider the various qualities (i.e., biodiversity) of the food we harvest in an eco-exergy context, we begin to get a more comprehensive view of agriculture's aggregated energy use. Eco-exergy has largely been used to evaluate aquatic ecosystems (Jørgensen, 2007; Xu et al., 2011; Marchi et al., 2011), but has also been used to evaluate other ecosystems such as forests (Lu et al., 2011) and even overall ecosystem dynamics (Zhang et al., 2010). Exergy itself, and even a socio-economic extension of exergy (Sciubba, 2001) dubbed extended exergy accounting, has also been used for assessing large, complex systems including energy and material flows through cities (Sciubba et al., 2008) and even whole countries (Dai et al., 2014; Chen et al., 2014). However, as exergy and extended exergy analyses do not account for varying qualities of energy within particular species (the qualities of energy we eat), and extended exergy analysis has a large economic consideration, eco-exergy was used for this explicitly biophysical analysis.

Industrialized intensive agriculture has minimized animate labor and increased efficiency by using considerably more supplementary energy than the Caloric energy accumulated. The energetics of agriculture have been a concern for decades (Fluck and Baird, 1980; Dovring, 1985; Fluck, 1992). Pimentel's (1984) energy input–output (I/O) perspective as a measure of agricultural efficiency showed that fruits and vegetables require two Calories to yield one Calorie of output (we use the standard convention of capital C to denote food Calories where 1 food Calorie = 1000 chemist calories). Animal products can require 20 (for beef cattle) and up to 57 (for lamb) Calories of input energy for each Calorie of output (Pimentel et al., 2008); generally, meat production entails a higher energetic toll on the environment than non-meat production (Pimentel, 1984; Pimentel and Pimentel, 2007; Pelletier, 2010; Pelletier et al., 2011; Subak, 1999) (note, these ratios are the reciprocal of EROI, e.g., I/O = 20 for beef cattle, then EROI = 1/20 = 0.05). While some of this additional energy is due, in part, to the non-meat plant kingdom operations required to feed the downstream husbandry operations, many of the activities (e.g., growing, transportation) included in the non-meat supply chain are identical in the meat supply chain. To provide a degree of separation for the meat energetics, we consider a new meat index (M_e) wherein we divide the embodied energy of meat products with the embodied energy of non-meat products (i.e., meat/non-meat). Similarly, dividing meat eco-exergy content by non-meat eco-exergy content creates M_x. This normalizes a society's meat production activities over-and-above its non-meat agricultural activities. For example, when comparing two M_e ratio calculations from two different food supply systems (e.g., one country versus another), the lower of the two would suggest a system of production (and perhaps corresponding demand) that is both more plant based and also more energy efficient at capturing the macronutrients provided by the animal kingdom (e.g., high density protein) for a society's food supply chain. The energetic consequences and inefficiencies attributed to a country's non-meat products are generally neutralized in this ratio and thus help a country focus on its meat supply system positives and negatives. Given the energy intensity attributed to animal products, a lower M_e ratio demonstrates a more energy-sustainable use of husbandry operations to provide a community's nutrients.

Embodied energy analysis reveals the energy expended in order to create the food products, and eco-exergy analysis reveals both the energy and quality of energy that the food product itself possesses; together, these measures provide a more complete energy profile of various food systems throughout the world. Further, a meat/non-meat ratio of these metrics begins to isolate animal nutrient production, a particularly energy intensive aspect in the food supply of a modernizing economy. We compare these metrics to two established and more widely recognized indicators of overall sustainability including ecological footprint and biocapacity to help place the anthropocentric food supply in a natural resources based context. The Global Footprint Network utilizes ecological footprint and biocapacity to measure the sustainability of human living. Ecological footprint (represented as global ha/person yr is generally considered a measure of demand and accounts for energy, settlement, timber and paper, food and fiber, etc. to calculate the amount of land necessary to both provide these resources and to absorb the associated wastes. Biocapacity (also represented as global ha/person yr) is generally considered a measure of supply and refers to the capacity of our ecosystem to provide biological resources and absorb carbon dioxide wastes given current management and extraction methods (Global Footprint Network, 2013). Together, these factors effectively measure the demand for resources from our environment and the supply it is capable of affording. Considered this way, sustainability, at least regionally, can be achieved when ecological footprint is less than or equal to biocapacity. This will be the definition of sustainability adopted for the rest of the paper.

2. Methods

2.1. Energy analysis

Varying qualities of data approximating diet choices and average Calories consumed were compiled for nine countries including Australia, Iran, Thailand, the United States, India, the United Kingdom, Cameroon, Egypt, and Tanzania. Eqs. (1)–(7) show how the embodied energy ratios are defined and compiled from the requisite data. In particular, Eqs. (1) and (2) define the I/Os calculated for each country for meat (subscript m) and non-meat (subscript n), Eqs. (3) and (4) define the number of calories consumed, and Eqs. (5) and (6) define the embodied energies. Eq. (7) defines the embodied energy meat index (M_e), which normalizes the meat production with respect to the non-meat production:

$$(\mathrm{I/O})_m = \frac{\text{total energy input to meat production}}{\text{total Caloric meat energy produced}} \tag{1}$$

$$(\mathrm{I/O})_n = \frac{\text{total energy input to non-meat production}}{\text{total Caloric non-meat energy produced}} \tag{2}$$

$$\mathrm{Cal}_m = (\text{fraction of meat Calories consumed daily}) \times (\text{total Calories consumed daily}) \tag{3}$$

$$\mathrm{Cal}_n = (\text{fraction of non-meat Calories consumed daily}) \times (\text{total Calories consumed daily}) \tag{4}$$

$$m = \text{embodied energy meat production} = \mathrm{Cal}_m \times (\mathrm{I/O})_m \tag{5}$$

$$n = \text{embodied energy non-meat production} = \mathrm{Cal}_n \times (\mathrm{I/O})_n \tag{6}$$

$$M_e = \text{embodied energy meat index} = \frac{m}{n} \tag{7}$$

Food system energy I/O analyses for Australia, Iran, Thailand, the United States, India, and the United Kingdom were averages of several EROI's published in the literature (Fluck, 1979; Watt, 1984; Tripathi and Sah, 2001; Chamsing et al., 2006; Pimentel and Pimentel, 2007; Beheshti Tabar et al., 2010). For example, to obtain the energy I/O ratio for cereal in Iran, the published EROI values of wheat, barley, and maize were weighted by the contribution (by weight) of each cereal to Iran's total cereal production. In addition to these calculations, in Iran, Thailand, India, and the United Kingdom, values for energy I/O ratios could not be obtained for beef, pork, poultry, and mutton, so an average value was used from the studies reported in Pimentel and Pimentel (2007). Absent published energy I/O values for Egypt, Cameroon and Tanzania, they were calculated using FAOSTAT food and agricultural commodities production data and the World Energy Council's agricultural energy intensity values (FAO, 2013; World Energy Council, 2013). Each country's meat index M_e is calculated as shown in Table 1.

2.2. Eco-exergy analysis

A per capita annual eco-exergy expenditure for consuming requisite quantities of each of eight food groups (cereals; roots and tubers; beef; pork; poultry; mutton; vegetables, fruits, pulses and nuts; oils, fats and sugars) was calculated for each country using Eq. (8) (Ludovisi and Jørgensen, 2009; Jørgensen, 2010; Jørgensen et al., 2010):

$$\text{Eco-Exergy density} = \sum_{i=1}^{n} \beta_i c_i \tag{8}$$

In this case, the concentration c_i is the biomass consumed per food group (i.e., kg/person yr) and β_i is the food group's specific weighting factor (i.e., magnifier) that accounts for the information contained in the genome of this food (Table 2). In order to construct the proteins responsible for various enzymatic life processes, an organism's genome must first be properly transcribed and translated. Larger β_i values quantify larger amounts of genome information embedded in a particular biomass, implying greater organism complexity and, generally, importance in biological assemblages (Jørgensen et al., 2005). The β_i values shown in Table 2 are normalized on the basis of detritus, or decomposed organic matter (i.e., β_i = 1 for detritus) as is Eq. (8). Thus, by definition, the eco-density in Eq. (8) must be multiplied by the chemical exergy content of detritus, 4469.4 Cal/kg as

Table 1
Nine country's embodied energy meat index calculation.

	Cereals	Roots and tubers	Meat, fish, milk, eggs				Fruits, vegetables, pulses, nuts	Oils, fats, sugars
			Beef	Pork	Poultry	Mutton		
Australia								
Calories consumed	798	319	404	214	365	133	160	798
Energy I/O	0.23	0.52	1.15	1.72	4.17	2.63	2.18	0.51
Embodied energy input (Cal/person yr)	65,560	60,546	1,69,660	1,34,558	5,55,635	1,27,691	1,26,709	1,49,397
								2.46
							M_e:	
Iran								
Calories consumed	1976	152	29	0	91	32	152	456
Energy I/O	0.74	0.95	12.01	5.23	1.93	21.44	1.53	0.51
Embodied energy input (Cal/person yr)	5,33,735	52,890	1,26,784	0	64,442	2,47,913	85,101	85,423
							M_e:	0.58
Thailand								
Calories consumed	1392	127	19	58	49	0	380	380
Energy I/O	0.28	0.11	12.01	5.23	1.93	21.44	1.53	0.10
Embodied energy input (Cal/person yr)	1,42,955	5074	85,440	1,10,772	34,531	0	2,12,473	13,715
							M_e:	0.62
United States								
Calories consumed	943	189	318	229	392	4	566	1320
Energy I/O	0.29	0.48	12.01	5.23	1.93	21.44	1.01	0.51
Embodied energy input (Cal/person yr)	1,00,899	33,078	13,94,456	4,37,111	2,76,088	29,568	2,07,545	2,47,184
							M_e:	3.63
India								
Calories consumed	1495	115	56	15	22	22	345	230
Energy I/O	1.12	3.08	12.01	5.23	1.93	21.44	1.38	0.51
Embodied energy input (Cal/person yr)	6,09,819	1,29,073	2,43,857	28,322	15,696	1,74,149	1,73,588	43,086
							M_e:	0.48
United Kingdom								
Calories consumed	860	172	222	282	295	62	172	1204
Energy I/O	0.96	1.16	1.68	2.85	1.93	1.42	1.72	0.51
Embodied energy input (Cal/person yr)	3,01,945	72,760	1,36,455	2,92,852	2,07,848	31,833	1,08,273	2,25,547
							M_e:	0.94
Cameroon								
Calories consumed	791	339	60	12	21	20	565	339
Energy I/O	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00
Embodied energy input (Cal/person yr)	294	147	319	46	56	106	901	159
							M_e:	0.35
Egypt								
Calories consumed	2,054	158	82	0	70	5	316	474
Energy I/O	0.41	0.11	0.76	0.00	0.38	0.60	0.64	0.09
Embodied energy input (Cal/person yr)	3,11,030	6332	22,675	0	9542	1036	73,313	16,218
							M_e:	0.08
Tanzania								
Calories consumed	909	505	72	4	13	12	303	101
Energy I/O	0.05	0.03	0.14	0.14	0.38	0.60	0.14	0.11
Embodied energy input (Cal/person yr)	18,188	5714	3732	187	1815	2627	15,203	3989
							M_e:	0.19

shown in Eq. (9):

$$\text{Eco-Exergy} = 4469.4\,\text{Cal/kg}\sum_{i=1}^{n}\beta_i c_i \tag{9}$$

to calculate the eco-exergy (Calories) for various biomass types (Jørgensen et al., 2005). Stated another way, the eco-exergy of one kg of detritus is 4469.4 Calories (i.e., $\beta_i = 1$). The eco-exergy of other biomass types increases as the weighting factor β_i of the respective biomass increases. For this analysis, Eq. (9) generates the eco-exergy consumed per individual per year for each country. The magnitude of this number quantifies the consequence of each country's biomass consumption within the greater biosphere's biomass diversity. The daily per capita Calories of each food group consumed for each country (FAO, 2013) and the energy density (Cal/kg) of each food group (Calorie Count, 2013) were used to calculate the nine countries' total energy density of each of the eight food groups. We adjusted for each country by weighting the energy densities of the foods that each country produced. For example, Thailand produces rice (3555 Cal/kg, 88% of production by mass) and maize (805 Cal/kg, 12% of production by mass) where Thailand's cereal energy density equals (3555 Cal/kg * 0.88) + (805 Cal/kg * 0.12) = 3225 Cal/kg.

Table 2
β_i-Values used in eco-exergy meat index calculations (Jørgensen et al., 2005).

Food type	β_i-Value	Organism
Cereal	275	Rice
Roots and tubers	393	Flowering plants
Beef	2138	Mammals
Pork	2138	Mammals
Poultry	980	Birds
Mutton	2138	Mammals
Fruits, vegetables, pulses, nuts	393	Flowering plants
Oils, fats, sugars	393	Flowering plants

Per Eq. (9), the annual per capita biomass consumed from each food was used to calculate the annual per capita aggregate eco-exergy consumed for each country (Cal/person yr). Similar to the embodied energy analysis, we compare the eco-exergy of meat to non-meat as a ratio (eco-exergy meat index M_x), shown in Eq. (10):

$$M_x = \text{eco-exergy meat index} = \frac{\left(\sum_{i=1}^{n}\beta_i c_i\right)_m}{\left(\sum_{i=1}^{n}\beta_i c_i\right)_n} \tag{10}$$

to normalize the eco-exergy expenditures of meat products beyond the non-meat products in the respective country's food supply system. Each country's results are calculated as shown in Table 3.

The total embodied energy input, total eco-exergy content, and the meat indexes M_e and M_x were compared to each country's ecological footprint and biocapacity (Global Footprint Network, 2007). To test for correlation and significance, linear regressions and Mann–Whitney-*U* tests were performed, respectively. The linear regressions were performed in Excel® and the Mann–Whitney-*U* tests were performed using an Excel® spreadsheet

Table 3
Nine country's eco-exergy meat index calculation.

	Cereals	Roots and tubers	Meat, fish, milk, eggs				Fruits, vegetables, pulses, nuts	Oils, fats, sugars
			Beef	Pork	Poultry	Mutton		
Australia								
Calories consumed daily	798	319	404	214	365	133	160	798
Energy density (Cal/kg)	3497	931	1859	1435	1971	2340	1634	1175
Biomass (kg) consumed annually	83	125	79	54	68	21	36	248
β^*biomass (kg)	22,891	49,170	1,69,756	1,16,277	66,304	44,334	14,004	97,373
Eco-exergy (Cal/person-year)	10,23,08,290	21,97,58,790	75,87,10,480	51,96,87,356	29,63,40,164	19,81,46,496	6,25,91,262	43,51,97,503
							M_x:	2.16
Iran								
Calories consumed daily	1976	152	29	0	91	32	152	456
Energy density (Cal/kg)	3531	588	1859	1435	1971	2340	428	497
kg consumed annually	204	94	6	0	17	5	130	335
β^*biomass (kg)	56,164	37,063	12,144	0	36,181	10,567	50,913	1,31,501
Eco-exergy (Cal/person-year)	10,50,272	6,93,073	2,27,101	0	6,76,588	1,97,602	9,52,070	24,59,074
							M_x:	0.21
Thailand								
Calories consumed daily	1392	127	19	58	49	0	380	380
Energy density (Cal/kg)	3219	1602	1859	1435	1971	2340	855	488
Biomass (kg) consumed annually	158	29	4	15	9	0	162	284
β^*biomass (kg)	43,385	11,327	8184	31,561	19,388	0	63,693	1,11,527
Eco-exergy (Cal/person-year)	8,11,297	2,11,822	1,53,044	5,90,183	3,62,548	0	11,91,056	20,85,550
							M_x:	0.26
United States								
Calories consumed daily	943	189	318	229	392	4	566	1320
Energy density (Cal/kg)	1290	568	1859	1435	1971	2340	976	891
Biomass (kg) consumed annually	267	121	62	58	73	1	211	541
β^*biomass (kg)	73,346	47,582	1,33,573	1,24,539	1,55,010	1260	83,079	2,12,453
Eco-exergy (Cal/person-year)	13,71,562	8,89,780	24,97,812	23,28,884	28,98,680	23,567	15,53,585	39,72,869
							M_x:	1.00
India								
Calories consumed daily	1495	115	56	15	22	22	345	230
Energy density (Cal/kg)	3342	885	1859	1435	1971	2340	1029	817
Biomass (kg) consumed annually	163	47	11	4	4	3	122	103
β^*biomass (kg)	44,897	18,641	23,359	8069	8813	7423	48,079	40,406
Eco-exergy (Cal/person-year)	8,39,578	3,48,585	4,36,808	1,50,899	1,64,795	1,38,808	8,99,068	7,55,584
							M_x:	0.31
United Kingdom								
Calories consumed daily	860	172	222	282	295	62	172	1204
Energy density (Cal/kg)	3536	554	1859	1435	1971	2340	604	1821
Biomass (kg) consumed annually	89	113	44	72	55	10	104	241
β^*biomass (kg)	24,416	44,565	93,219	1,53,148	1,16,696	20,534	40,874	94,832
Eco-exergy (Cal/person-year)	4,56,571	8,33,366	17,43,188	28,63,870	21,82,214	3,83,986	7,64,340	17,73,352
							M_x:	1.87
Cameroon								
Calories consumed daily	791	339	60	12	21	20	565	339
Energy density (Cal/kg)	1918	1401	1859	1435	1971	2340	1419	1534
Biomass (kg) consumed annually	151	88	12	3	4	3	145	81
β^*biomass (kg)	41,396	34,709	25,200	6401	8389	6673	57,132	31,704
Eco-exergy (Cal/person-year)	7,74,106	6,49,062	4,71,238	1,19,701	1,56,868	1,24,791	10,68,376	5,92,870
							M_x:	0.28
Egypt								
Calories consumed daily	2054	158	82	0	70	5	316	474
Energy density (Cal/kg)	2671	510	1859	1435	1971	2340	387	468
Biomass (kg) consumed annually	281	113	16	0	13	1	298	369
β^*biomass (kg)	77,182	44,434	34,489	0	27,525	1581	1,17,013	1,45,174
Eco-exergy (Cal/person-year)	14,43,298	8,30,917	6,44,946	0	5,14,713	29,560	21,88,136	27,14,749
							M_x:	0.17
Tanzania								
Calories consumed daily	909	505	72	4	13	12	303	101
Energy density (Cal/kg)	1980	1224	1859	1435	1971	2340	1979	1663
Biomass (kg) consumed annually	168	151	14	1	2	2	56	22
β^*biomass (kg)	46,071	59,160	30,284	1962	5237	4010	21,961	8710
Eco-exergy (Cal/person-year)	8,61,519	11,06,293	5,66,312	36,682	97,924	74,984	4,10,675	1,62,886
							M_x:	0.31

Table 4
Embodied energy input and eco-exergy content of nine countries' food systems.

Country	Embodied energy input (MJ/person yr)	Country	Eco-exergy content (MJ/person yr)
United States	11,405	United States	15,536,738
India	5931	United Kingdom	11,000,887
Australia	5815	Australia	10,848,026
United Kingdom	5764	Egypt	8,366,319
Iran	5005	Iran	6,255,780
Thailand	2531	Thailand	5,405,501
Egypt	1842	Cameroon	3,957,011
Tanzania	215	India	3,734,124
Cameroon	8	Tanzania	3,317,277

Table 5
Embodied energy and eco-exergy meat indexes for nine countries' food systems.

Country	Embodied energy meat index (M_e)	Country	Eco-exergy meat index (M_x)
United States	3.63	Australia	2.16
Australia	2.46	United Kingdom	1.87
United Kingdom	0.94	United States	1.00
Thailand	0.62	Tanzania	0.31
Iran	0.58	India	0.31
India	0.48	Cameroon	0.28
Cameroon	0.35	Thailand	0.26
Tanzania	0.19	Iran	0.21
Egypt	0.08	Egypt	0.17

provided by Holah Karoo (2013). A Mann–Whitney-*U* test was used because it is a more efficient auditor of smaller datasets and non-normal distributions than a *t*-test.

Finally, we explored what the theoretical maximum M_e and M_x values should be for each country (i.e., $M_{e,theoretical\ max}$ and $M_{x,theoretical\ max}$), how these compare to the observed M_e and M_x values (calculated in Tables 1 and 3, respectively), and what changes can be made to the observed values to become more sustainable. Specifically, assuming local energy sustainability is achieved when a country's ecological footprint is equal to or less than its biocapacity (i.e., demand $\leq$ supply), we used the equation of the best-fit line produced by the linear regression analysis where ecological footprint is predicted by M_e or M_x, respectively. However, instead of using ecological footprint as y to predict x, we used biocapacity values for each country to calculate an x (i.e., $M_{e,theoretical\ max}$ and $M_{x,theoretical\ max}$) that corresponds to the biocapacity available. This determines a theoretical maximum threshold of M_e and M_x which, if exceeded, will result in a country using more than their available resources. We calculated the difference between the observed and theoretical maximums of M_e and M_x (defined as $((M_{e,theoretical\,max} - M_{e,observed})/M_{e,observed}) \times 100$) and compared this with the difference between ecological footprint and biocapacity (defined as (biocapacity-ecological footprint/ecological footprint) $\times$ 100). With this, a negative difference would indicate that the observed ratios or ecological footprint are less than the theoretical maximum ratios or biocapacity. For example, if a country had a difference between ecological footprint and biocapacity of −40%, that country must decrease its ecological footprint by 40% to match its available biocapacity. In addition, we tested and discussed the various factors affecting M_e and M_x and which of these factors had the largest influence on their values.

3. Results

Table 4 shows the embodied energy [Eqs. (5) and (6)] and the eco-exergy content [Eq. (9)] of nine countries' food systems thereby quantifying both the quantity of energy consumed by their food production and the relative importance, in an ecosystem sense, of the energy dissipated. Broadly interpreted, the country rankings for each metric were similar in some respects. Australia, the United Kingdom, and the United States are the highest. Iran and Thailand are in the middle, and Cameroon and Tanzania are near the lowest. Cameroon has a very low embodied energy input compared to the rest of the countries. However, this is consistent with its minuscule agricultural energy intensity of 0.001 koe/$05p (kg of oil eq./0.5 penny GDP) in 2011; this is 41 times less than Tanzania's agricultural energy intensity, and 116 times less than the United States' (World Energy Council, 2013). Table 5 shows the embodied energy and eco-exergy meat indexes, Eqs. (7) and (10), wherein the total values of embodied energy input and eco-exergy content for meat products in each country are normalized respectively by the total embodied energy input and eco-exergy content for non-meat products. Again, the United Kingdom, Australia, and the United States have the highest magnitudes. Egypt interestingly has the lowest in both, and the remaining countries are a bit mixed in the energetics of their food supply representation. Theoretically, countries with a higher quantity of meat in their diet would require greater embodied energy inputs to supply those meat products, and the meat products would also garner a larger β_i-value, thus inflating both ratios. Table 6 shows the percentage of meat in each of these country's diets. The United Kingdom, Australia, and the US are a full order of magnitude higher in percentage of meat in their diets (25–35%) as compared with the remaining six countries (5%), which begins to articulate their dominance in both Tables 4 and 5.

Iran has a relatively high total eco-exergy content in its food production system, yet its M_x content is the second lowest of the nine countries. This is predominantly due to the low percentage of meat Calories in its diet. However, other factors responsible for changes in ranking can be traced to the differences in the Caloric density of the various foods produced. For instance, 68% of the Calories consumed in Iran are derived from grains, yet grains only comprise 25% of the total weight of food consumed. This indicates that their diet is very energy rich (i.e., high ratio of Cal/kg). Comparatively, of Tanzania's total Calories consumed, a lower 47%, are derived from grains and 26% by roots and tubers. Of the total weight of food consumed annually, 40% by weight are grains and 36% by weight are roots and tubers (i.e., lower ratio of Cal/kg). This helps explain Iran's high total eco-exergy content and low M_x and, conversely, Tanzania's low total eco-exergy content yet high M_x.

Figs. 1 and 2, respectively, consider the relationship of the total embodied energy [Eqs. (5) and (6)] and eco-exergy [Eq. (9)] of each country's food supply to their respective ecological footprint and biocapacity. The meat indexes for embodied energy M_e and eco-exergy M_x were compared to their respective country's ecological footprint and biocapacity in Figs. 3 and 4. Interestingly, Australia is always an outlier (Figs. 1B, 2B, 3B, and 4B) due to its relatively high biocapacity, which is at least partially attributed to how biocapacity is represented on a per capita basis. In 2010 for

Table 6
Percent of meat comprising each of nine countries' diets.

Country	% meat
Australia	35
United Kingdom	25
United States	25
Cameroon	5
Egypt	5
India	5
Iran	5
Tanzania	5
Thailand	5

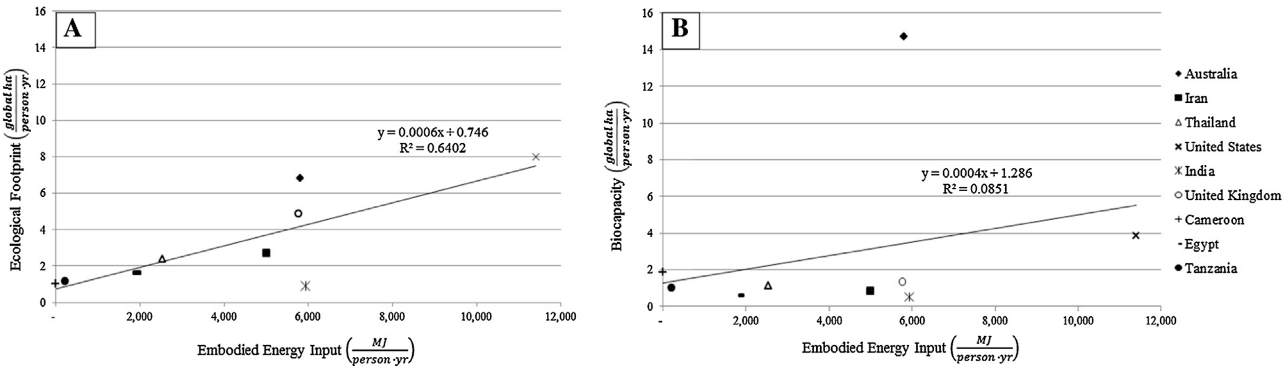

Fig. 1. Annual per capita embodied energy of each country's food system compared to the annual per capita ecological footprint (A) and biocapacity (B) of that country.

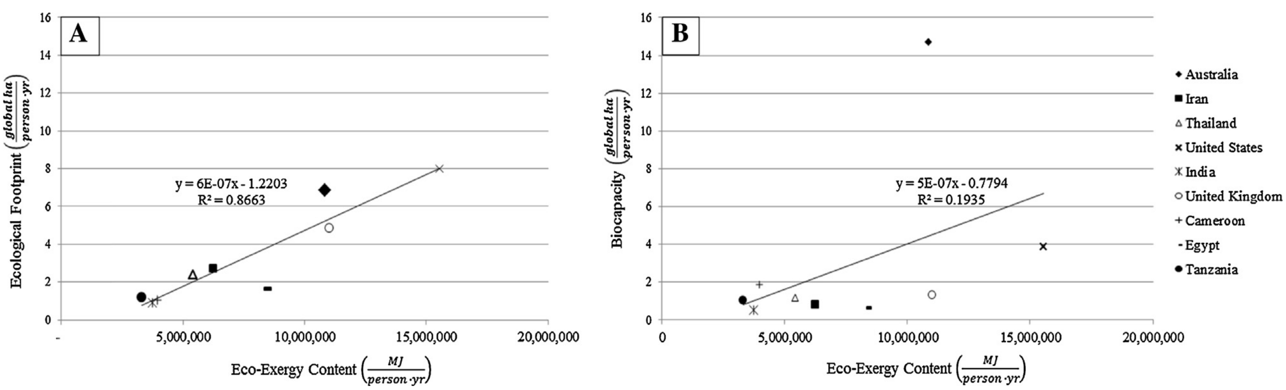

Fig. 2. Annual per capita eco-exergy content of each country's food system compared to the annual per capita ecological footprint (A) and biocapacity (B) of that country.

example, compared to the US (35 people/km^2 land), Australia was a low 3 people/km^2 land (The World Bank, 2015). Additionally, in Fig. 4A the US is also an outlier. This is due to the US' relatively high ecological footprint, yet relatively low calculated value of M_x. Table 7 shows the goodness of fit for each best-fit line in Figs. 1–4 (i.e., R^2) and also the Mann–Whitney-U confidence in each R^2 value. These results suggest that the energetics of a country's food supply are correlated in many ways to their respective ecological footprint (i.e., a country's annual per capita impact on the environment). With Mann–Whitney-U confidences of 98% for each best-fit line, the total embodied energy and eco-exergy invested in food production, along with the meat index ratios M_e and M_x, are all strongly correlated with ecological footprint (R^2 = 0.64, 0.87, 0.88, and 0.60 respectively). To the contrary, the food supply energetics are poorly connected to the respective country's biocapacity (i.e., ability of the ecosystem to provide these products). The highest correlation with biocapacity was M_x with R^2 = 0.55 and a Mann–Whitney-U confidence of 90%. This implies that the biocapacity of a region (its ability to supply sufficient energy for the food production system) must then be subsidized to account for the lack of naturally supplied energy and eco-exergy. It is presumed this differential is primarily provided by fossil fuels. These results confirm that these countries are exceeding the limits on their available biocapacity (i.e., decoupled and no correlation), facilitating this with fossil or other supplementary fuels, and ultimately increasing their ecological footprint (i.e., coupled and reasonably correlated) in fairly substantial ways.

We determine the theoretical maximum M_e and M_x ratios if ecological footprint (demand) was exactly equal to biocapacity (supply) for each country. Using the best-fit linear equations between ecological footprint and M_e and M_x from Figs. (3A) and (4A), respectively, we substitute in each country's biocapacity (as the y value, replacing ecological footprint) and then calculate the

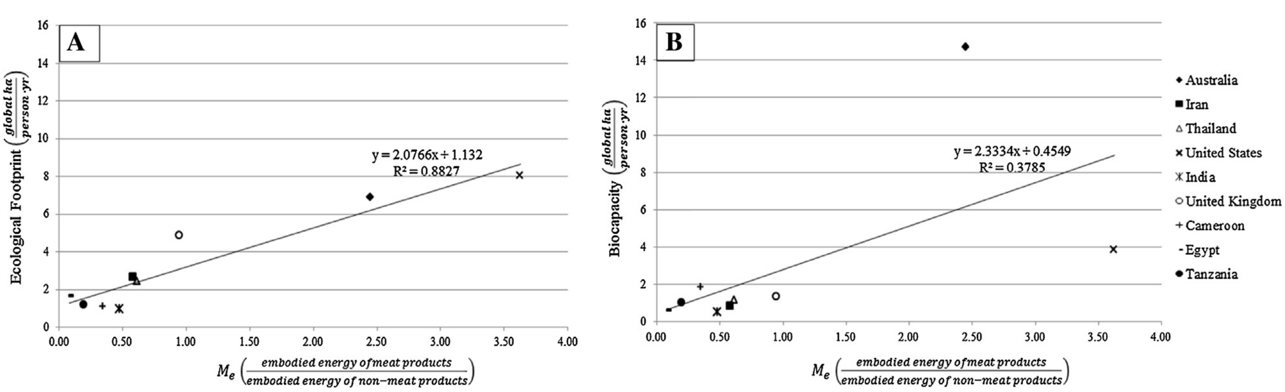

Fig. 3. Embodied energy meat index (M_e) of each country compared to the annual per capita ecological footprint (A) and biocapacity (B) of that country.

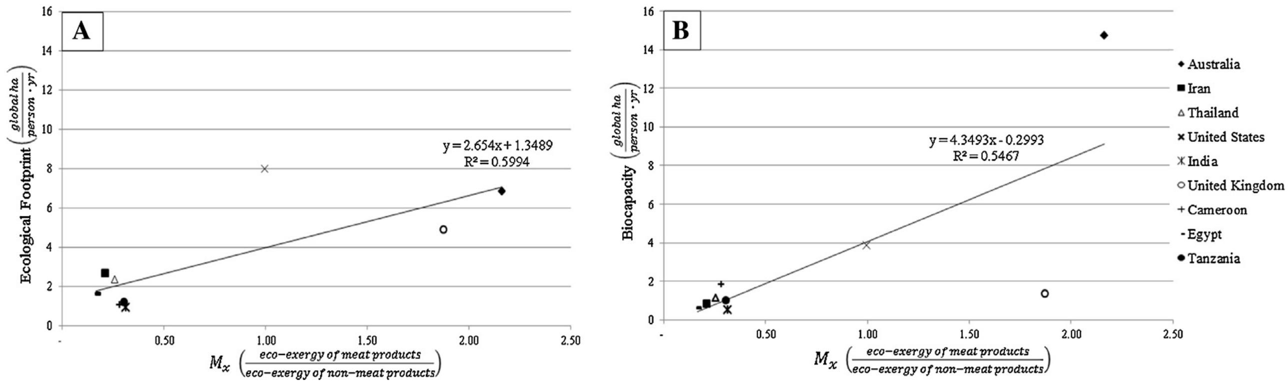

Fig. 4. Eco-exergy meat index (M_x) of each country compared to the annual per capita ecological footprint (A) and biocapacity (B) of that country.

Table 7
Summary table of linear regression and significance test results for relationships depicted in Figs. 1–4.

Figure	Relationship	R^2	% confidence level
3A	M_e vs. ecological footprint	0.88	98
2A	Eco-exergy content vs. ecological footprint	0.87	98
1A	Embodied energy vs. ecological footprint	0.64	98
4A	M_x vs. ecological footprint	0.60	98
4B	M_x vs. biocapacity	0.55	90
3B	M_e vs. biocapacity	0.38	90
2B	Eco-exergy vs. biocapacity	0.19	98
1B	Embodied energy vs. biocapacity	0.09	98

corresponding $M_{e,theoretical\ max}$ and $M_{x,theoretical\ max}$. Given a country's biocapacity, these theoretical maximum M_e and M_x values represent the threshold to which any M_e and M_x magnitudes that exceed these are above the country's carrying capacity. Table 8 depicts these results. For example, Australia's theoretical maximum M_e is calculated from $y = 2.077(M_{e,theoreical\ max}) + 1.132$, where y is the biocapacity at 14.71 global ha/person. Note that a negative theoretical maximum M_e or M_x as calculated from the ecological footprint linear equation line (using the biocapacity for y) results from a biocapacity lower than the y-intercept of the best-fit line (e.g. 1.132 in the above equation). In other words, if a country's biocapacity was exactly equal to 1.132, its $M_{e,\ theoretical\ max}$ would be 0; any biocapacity less than 1.132 results in a negative $M_{e,\ theoretical\ max}$. However, the y-intercept has no statistical significance in these results as the Mann–Whitney-U tests the confidence in x as a predictor of y (i.e. the slope of the best-fit line), both of which are at 98% confidence for Figs. (3A) and (4A). A negative theoretical maximum M_e or M_x has no physical significance as we have not tested for confidence in the y-intercept; therefore it is the difference between the observed and theoretical maximum M_e and M_x that is relevant. Fig. 5 compares the differences between the observed M_e and $M_{e,\ theoretical\ max}$, the observed M_x and $M_{x,\ theoretical\ max}$, and the ecological footprint and biocapacity for each country, essentially showing the difference between the observed and sustainable values for each of these measures.

4. Discussion

Despite man's vast use of energy for housing, industry, and transportation, at the most fundamental level, as a member of the animal kingdom, mankind's energetic relationship to the biosphere is through his food supply. As such, sustainably acquiring food is one of the most important steps mankind can take as he begins to address his imbalance with the environment. To pursue a better understanding of the complex food harvesting of an increasingly stressed, biodiverse world, we uniquely quantified this food supply relationship for nine countries to help elicit both the quality and quantity of Caloric energy flow as compared to a country's biocapacity and current level of sustainability (i.e., ecological footprint). Given the global reach of this project, data gaps and inequalities were encountered which can be considered normal for energy centric projects of this nature. For example, EROI studies in the agricultural literature vary with their inclusion of indirect energy inputs, or their inclusion of meat production. Also,

Table 8
Equations and results of calculating $M_{e,theoretical\ max}$ and $M_{x,theoretical\ max}$, and the difference between old (ecological footprint, observed M_e and observed M_x) and new (biocapacity, theoretical maximum M_e and theoretical maximum M_x, respectively) values.

Country	Ecological footprint (global ha/person)	Biocapacity (global ha/person)	Difference	Equation used (from Fig. 3A) $y = 2.077 + 1.132$			Equation used (from Fig. 4A) $y = 2.654x + 1.349$		
				Observed, M_e	Theoretical maximum, M_e	Difference	Observed, M_x	Theoretical maximum, M_x	Difference
Australia	6.84	14.71	115%	2.46	6.54	166%	2.16	5.04	133%
Iran	2.68	0.81	−70%	0.58	−0.16	−126%	0.21	−0.20	−194%
Thailand	2.37	1.15	−51%	0.62	0.01	−98%	0.26	−0.07	−129%
United States	8.00	3.87	−52%	3.63	1.32	−64%	1.00	0.95	−5%
India	0.91	0.51	−44%	0.48	−0.30	−162%	0.31	−0.32	−201%
United Kingdom	4.89	1.34	−73%	0.94	0.10	−89%	1.87	−0.00	−100%
Cameroon	1.04	1.85	77%	0.35	0.35	−1%	0.28	0.19	−33%
Egypt	1.66	0.62	−63%	0.08	−0.25	−403%	0.17	−0.28	−266%
Tanzania	1.18	1.02	−14%	0.19	−0.06	−129%	0.31	−0.13	−141%

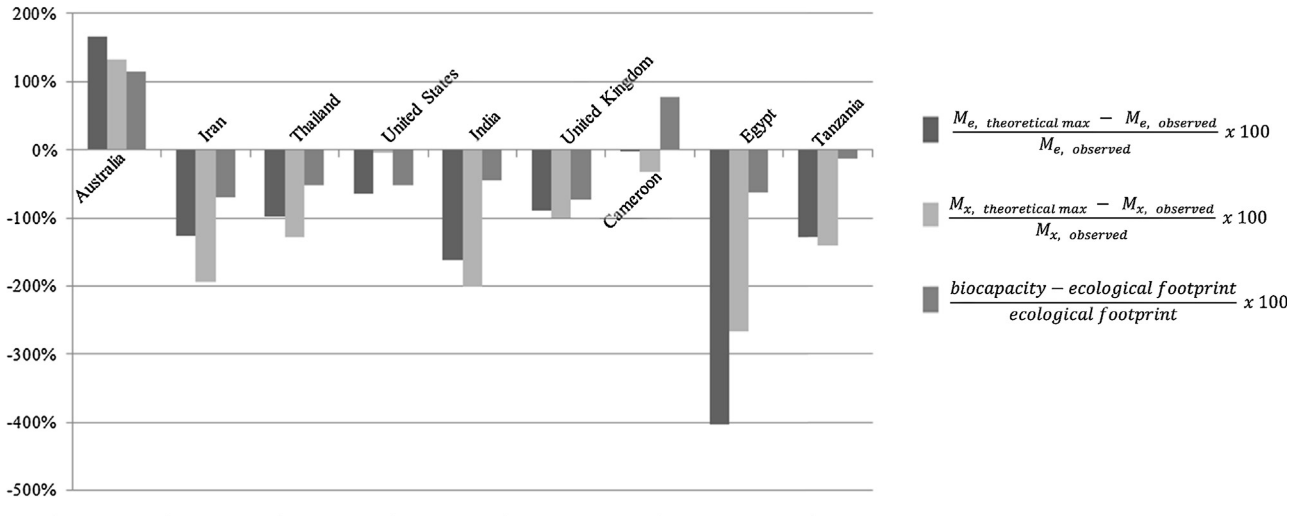

Fig. 5. Difference between observed M_e (embodied energy of meat products/embodied energy of non-meat products) and theoretical maximum M_e, observed M_x (eco-exergy of meat products/eco-exergy of non-meat products) and theoretical maximum M_x, and ecological footprint and biocapacity for each country.

considering our data, there is a 31-year gap between the earliest (1979) and most recent (2010) date of publication necessarily used for our calculations. However, each of these shortcomings was addressed with numerical methods, similar substitutions, and general methods common in the literature. Given the importance of these results and their supporting data, these data issues must be overcome with judicious engineered substitutions or progress in agricultural sustainability will be stunted.

Eco-exergy is an excellent quantifier of biomass importance in a hierarchical networked biosphere. However, its use in ecosystem management is still novel (Zhang et al., 2010; Xu et al., 2011; Marchi et al., 2011). The literature carefully notes that this metric includes the upstream work energy that is embodied in the information (Jørgensen and Nielsen, 2014). Thus, it is an embodied energy calculation (not a chemical work energy) that nicely accounts for a hierarchical level of importance in the biodiversity of assemblage. Its use with sustainable agriculture would help correlate and then measure mankind's inclination for meat beyond what the biosphere is capable of supplying. Understood from this perspective, it is a reasonable metric for agricultural system management.

We calculated four measures of food energy expenditure: total embodied energy, total eco-exergy, embodied energy meat index (M_e), and eco-exergy meat index (M_x) and compared each with ecological footprint and biocapacity. Currently 30 percent of the world's total annual energy dissipation is dedicated to the agrifood system (FAO, 2012). From 1997 to 2002 the US per capita energy demand decreased by 1.8 percent while the per capita food-related energy demand increased by 16.4 percent, pushing total US energy use up 3.3 percent (Canning et al., 2010). Half of this increase in food-related energy is due to a shift from reliance on human labor to other energy sources (Canning et al., 2010). It is then logical that Table 7 shows that each of our four calculated measures all correlate more with ecological footprint than with biocapacity. With a food system that is increasingly reliant on supplement energy sources, it is reasonable that the quantity and quality of this energy would reflect measures of our superfluous demand (ecological footprint) rather than the supply available (biocapacity).

Though much progress in global food security has been made in recent decades, continuing to increase food availability without compromising biodiversity and environmental health remains a problem for the future (Hazell, 1999; Loreau et al., 2001). At the current rate of energy and resource consumption, we would need 1.5 earths to satisfy our annual global resource demand. This is a global estimate, however; while the US requires 5 planets, India only would need 0.4 (Global Footprint Network, 2014). This discrepancy emphasizes the importance of energy management plans specific to each country's needs. However, the simplicity of only one or two single indicators of agriculture and environmental health is also recognized (Bockstaller et al., 1997; Dale and Polasky, 2007). By comparing our M_e and M_x ratios to ecological footprint, a measure of each country's demand on its natural capital, we established a significant relationship between energy use in food systems and the overall situation of resources specific to each country. We used this relationship to determine what these M_e and M_x ratios must be if each country's demand on its natural capital matched its supply (i.e., the theoretical maximum M_e and M_x). Fig. 5 shows that the differences between observed M_e and $M_{e,theoretical\ max}$, observed M_x and $M_{x,\ theoretical\ max}$, and ecological footprint and biocapacity are all relatively similar for each country. This indicates that reducing M_e and M_x may be important steps toward bringing a country's ecological footprint more in line with the biocapacity that is actually available. Each country may then decide which aspects of these ratios are the most realistic and effective in shifting the overall ratio. For example, if the UK decreased its meat calories by 25% while simultaneously increasing its non-meat calories 25%, this would reduce its M_x by nearly 40%. If the US decreased its energy input/output ratio for meat by 25%, its M_e value would decrease by 25% as well. This shows which type of changes may be more or less feasible for each country to adjust their food energy profile and ultimately their overall environmental impact.

The International Food Policy Research Institute has modified its framework for agricultural development and growth in order to also ensure environmental stewardship. One of these modifications urges a broader resource management strategy but with localized implementation (Hazell, 1999). Our modified measures of the food energy attributed to meat production and their clear relationship to a country's ecological footprint have directly tied regional agricultural practices with overall resource management. Changing agricultural practices to ultimately adjust these metrics may directly improve ecosystem health. Thus, by simplifying various aspects of energy flow in agriculture into two measures, and by connecting these measures to indicators of overall ecosystem health, we have provided a relatively simple method to show countries on an individual basis both their food system's energetic imparity with their overall resource availability and also the various ways in which they can adjust their agricultural practices to more thoroughly represent the supporting ecosystem.

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