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Food Production Engineering Efficiency: A Critical Analysis of the Conventional Metrics Used in Measuring Agricultural Efficiency

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Abstract

An analysis is reported of conventional vs. alternative metrics used in measuring food production efficiency. Economic efficiency is driven by marketplace economics, while engineering efficiency is driven by useful energy conservation. As farming systems are optimized for maximum efficiency, how "efficiency" is defined will dictate the methods used in food production. Farming methods that are optimized in terms of economic efficiency have environmental consequences that are not inherent of engineering efficiency; however, farming methods optimized in terms of engineering efficiency have labor requirements not inherent of economic efficiency. A shift from optimizing food production in terms of economic efficiency to engineering efficiency may be necessary in order to feed a growing human population.

Keywords

Efficiency, Farming, Agriculture, Calories, Energy, Waste, Metrics, Measures

1. Introduction

With a growing human population, it is becoming increasingly important for potential food Calories (units of energy) to not go to waste. In optimizing food production efficiency, the definition of the metric "efficiency" must reflect a measure that is directly proportional to food availability, as opposed to marketplace economics. There is an opportunity to facilitate the optimization of production in terms of an efficiency metric that is independent of finance: engineering efficiency, η_{engr}, which is defined as useful energy output per total energy input. This is contrasted with economic efficiency, η_{econ}, defined as yield per cost. Mathematically, these definitions are [1]:

$$\eta_{\text{engr}} = \frac{\text{useful energy output}}{\text{total energy input}}. \tag{1}$$

$$\eta_{\text{econ}} = \frac{\text{profit}}{\text{cost}} \sim \frac{\text{yield}}{\text{cost}}. \tag{2}$$

Optimizing food production in terms of engineering efficiency as opposed to economic efficiency will mitigate challenges related to antibiotic resistance and eutrophication. The shift to the η_{engr} model will also help ensure that useful Calories are available to future generations. In order to keep up in the marketplace, farm businesses must optimize for economic efficiency; however, to maintain resources for the public at large, it will be necessary for optimization to occur in terms of engineering efficiency.

Practical application of the η_{engr} model necessitates the implementation of a Public framework, given the model's independence from marketplace economics. Proposed here is a legal infrastructure intended to serve in shifting farmers' food production optimization from η_{econ} to η_{engr}, without applying new regulations to the open market.

Livestock production is the focus of this proposal; however, it is the opinion of the author that the same principles of efficiency optimization can be carried over to any crop production.

2. Analysis

The farm has inputs and outputs (Figure 1). For the purposes of this proposal, inputs are simplified as time, money, and energy; outputs are simplified as produce, heat, and manure. Time and money are considered the conventional costs of production (e.g. labor, overhead, feed costs), while energy is the actual caloric input (e.g. electricity, fuel, feed sustenance); produce is the commodity that the farm is producing (e.g. milk, meat, eggs, vegetables), while heat and manure are byproducts. Water may be assumed to input with energy and output with manure.

In this paper, the example used is of meat production, which for time, money, and energy outputs meat, heat, and manure. The efficiencies analyzed will be optimized in terms of money (economic efficiency) vs. Calories (engineering efficiency). While "money" and "Calories" are not listed as a farm outputs, they do serve as inputs and are therefore appropriate units to use in analyzing efficiency, representing how much useful input can be extracted from a given system's output.

2.1. Efficiency Definitions

The definition of "efficient" dictates the measure of a system's efficiency. Conventionally, produce is maximized while costs (time & money) are minimized,

Figure 1. Generalized farm inputs (left) and outputs (right).

because farm business optimization is based on marketplace economics. For example, one 1000 lb steer will yield 310 lb beef* valued at approx. $2.30 per lb [2], returning the farmer $713.00. This same steer will output 21,900 lb of manure† [3], valued at approx. $10.84 per ton [4] [5], returning the farmer only $108.00:

$$\begin{aligned}&1000\ \text{lb/steer} \times 0.62\ \text{dressing weight/live weight}\\&\times 0.5\ \text{weight without fat \& bones/dressing weight} = 310\,\text{lb meat/steer}.\end{aligned} \tag{3}$$

$$\rightarrow 310\ \text{lb meat/steer} \times \$2.30/\text{lb meat} = \$713.00/\text{steer}. \tag{4}$$

$$\$10.84/\text{ton manure} \times 10\ \text{tons manure/steer} = \$108.00/\text{steer}\ . \tag{5}$$

The difference in dollar value between meat and manure as calculated above is displayed in **Figure 2** below. The farmer will maximize the production of meat, not manure, because the meat both is easier to transport and has a higher dollar value than that of manure. To optimize in terms of economic efficiency η_{econ}, meat production will be maximized while costs minimized; a cow that produces a relatively large amount of meat per feed and other costs are considered "efficient".

However, one pound of dry manure contains 8500 Btu (2150 Calories or kcal) [6] of energy, while one pound of beef contains 1200 Calories [7]. The 1000 lb steer will output over 7,000,000 Calories in its manure, assuming its ten tons of fertilizer dehydrate down to 3290 lb dry manure‡. At the same time, the steer's meat yields under 400,000 Calories:

$$3290\ \text{lb manure} \times 2150\,\text{Calories/lb manure} = 7060000\ \text{Calories from manure}. \tag{6}$$

$$310\ \text{lb beef} \times 1200\,\text{Calories/lb beef} = 372000\ \text{Calories from meat}. \tag{7}$$

The difference in caloric value between meat and manure as calculated above is displayed in **Figure 3** below. In terms of engineering efficiency η_{engr}, meat production is negligible and the dominant factor of efficiency is the useful recycling of manure; a cow whose manure is directly recycled as a useful input elsewhere is considered "efficient".

Optimizing to maximize meat production does not necessarily correlate to energy reuse maximization. In fact, regardless of how highly economic-efficient a steer is, it will only attain a 5% engineering efficiency§:

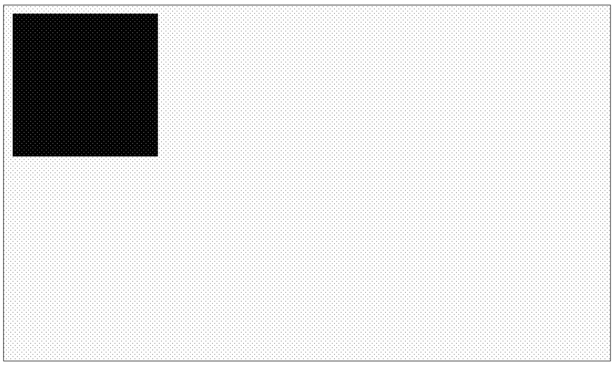

Figure 2. Relative market value per livestock head for meat (░) vs. manure (■).

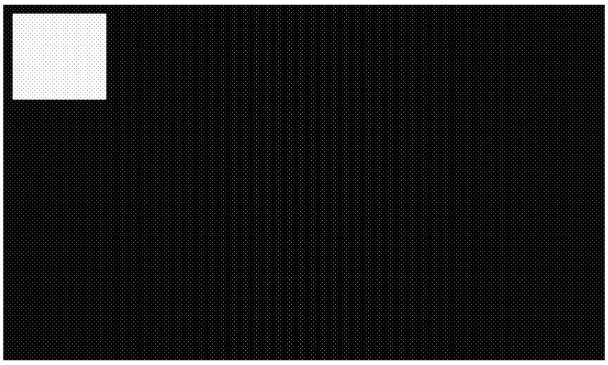

Figure 3. Relative energy value per livestock head for meat (░) vs. manure (■).

$$\eta_{\text{engr}} = \frac{372000 \text{ beef Calories}}{7060000 \text{ manure Calories}} = 0.0527 \cong 5\% \text{ efficiency.} \tag{8}$$

On the other hand, the greater percent of manure that is usefully recycled, the higher the engineering efficiency:

$$\eta_{\text{engr}} = \frac{372000 \text{ beef Calories} + \text{useful manure Calories}}{7060000 \text{ manure Calories} - \text{useful manure Calories}} \cong 5 \text{ to } 100\% \text{ efficiency} \tag{9}$$

Engineering efficiency recognizes the primary producer's primary function as soil building [8], with meat as a byproduct; economic efficiency recognizes the primary producer's primary function as meat production, with manure as a byproduct. One optimizing in terms of the Calorie; the other, the dollar.

*Assuming fat and bones are removed from a 62% dressing weight.

†Assuming a linear increase in weight from 0 to 1000 lb over a two-year growth period.

‡Assuming semi-solid manure containing 85% moisture [9].

§Assuming manure Calories equal feed Calories.

2.2. Farming Methods

Farming methods are determined by optimizing in terms of efficiency. The factory farm is more efficient in terms of η_{econ}, but the pasture is more efficient in terms of η_{engr}. Consider the pig: on a per-pig basis, hoop barns (pasture with shelter) require twice the labor—a major financial cost—than is required by factory farms (complete confinement) [10]. However, hoop barns are more energy efficient, demanding approximately 3.0 MJ/pig less than factory farms [11]. Additionally, manure from hoop barns [4] is valued three times higher than that from factory farms [5], based on its nutrient content:

Hoop Barn:

$$\begin{gathered}\left(35 \text{ lb N/ton N} \times \$0.225/\text{lb N}\right) + \left(20 \text{ lb P}_2\text{O}_5/\text{ton N} \times \$0.22/\text{lb P}_2\text{O}_5\right) \\ + \left(23 \text{ lb K}_2\text{O/ton K} \times \$0.12/\text{lb K}_2\text{O}\right) = \$15.035/\text{ton}.\end{gathered} \tag{10}$$

Feedlot:

$$\begin{gathered}\left(13 \text{ lb N/ton N} \times \$0.225/\text{lb N}\right) + \left(12 \text{ lb P}_2\text{O}_5/\text{ton N} \times \$0.22/\text{lb P}_2\text{O}_5\right) \\ + \left(9 \text{ lb K}_2\text{O/ton K} \times \$0.12/\text{lb K}_2\text{O}\right) = \$6.645/\text{ton}.\end{gathered} \tag{11}$$

Higher-value manure introduces economic incentive for its transport onto cropland, avoiding challenges related to on-farm nutrient stockpiling like eutrophication and antibiotic resistance.

2.3. Environmental Consequences

Economic-efficient farming methods have environmental consequences. In order to ensure that manure is valued as a nutritious compost, the appropriate metric must be used in optimizing the farming process. If an inappropriate metric is used, farming methods will be optimized without regard to useful recycling of energy outputs, and the value of manure can drop until it becomes a hazard: Public health threats, such as antibiotic-resistant Staphylococcus aureī like MRSA, fecal streptococci and coliforms [12] [13], and Escherichia coli [14], have been linked with factory farm nutrient outflows. It has also been shown that carrots and lettuce will uptake tetracycline and amoxicillin (two commonly used antibiotics) [15], further devaluing manure of the factory farm, making it less likely that the waste is to be recycled for useful applications.

Antibiotic-impregnated feed can be avoided by keeping livestock in healthy pastures with shelter: a low-stress, clean environment where exercise is possible and nutritious diet available [16] [17]. This harnesses animals' own immune systems to combat infectious diseases. On pasture, manure is a valuable resource that is recycled to fertilize subsequent years' vegetation.

2.4. Labor Considerations

Engineering-efficient farming methods have relatively high labor requirements. This is the problem at hand: pastured livestock production, however efficient in terms of η_{engr}, is not justified under η_{econ}, given its high labor demands. As the farm becomes more automated, substitutions have been made to replace human labor. While on the surface, these technologies appear to improve efficiency, because cost (time & money) inputs are reduced, the total energy required to achieve the same agricultural goal has been increasing with each new technology. This phenomenon is detailed in **Table 1** below. It is on the smaller farms, where families work with their hands to bring forth food from the earth, where engineering efficiency is maximized.

Table 1. Comparison of energy inputs for tilling 1.0 ha of soil [18].

Tilling Unit	Required Hours	Machinery Input (kcal)	Petroleum Input (kcal)	Hour/Day	Working Human/Hour Input (kcal)	Human Daily Energy Input (kcal)	Total Human Input (kcal)	Oxen Energy Input (kcal)	Total Input (kcal)
Human Power	400	6000	0	10	400	5400	216,000	0	222,000
Oxen (pair)	65	6000	0	10	375	5150	33,500	260,000	299,500
6-HP Tractor	25	47,500	237,600	10	200	3400	8500	0	293,600
50-HP Tractor	4	61,300	306,300	4	200	3400	1360	0	368,900

This consequential trend—labor reduction in the interest of economic efficiency, at the expense of engineering efficiency—may be continuing with more-recent innovations such as solar cells, which present ecological hazards through their mining and manufacture in countries with minimal environmental regulations [19]. It also might be argued that in the optimization of η_{econ} the human labor component has been reallocated to better uses; this may true in some cases, but not all. For example, consider the efficiency of fitness centers, where energy is outputted without accomplishing useful work.

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