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Energy efficiency in small-scale biointensive organic onion production in Pennsylvania, USA

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Abstract

Modern agriculture relies heavily on fossil energy for food production. Reducing fossil energy and replacing that energy with renewable energy is critical in attaining a sustainable food system. Hand-scale intensive food production offers a reduction in fossil energy and an increased use of renewable human-based energy. Using biointensive production techniques, onions (*Allium cepa*) were grown in Pennsylvania, USA. A life-cycle analysis was performed to monitor energy utilization. Individual human labor tasks were evaluated using the factor method. This method accounts for the type and duration of physical activity. The average yield of eight onion varieties utilizing biointensive production in standard-sized beds (9.3 m^2;100 ft^2) was 160.2 kg. The US average for mechanical onion production is 46.1 kg/9.3 m^2 (100 ft^2). The energy efficiency ratio, specific energy and energy productivity were 51.5, 0.03 MJ kg^{-1} and 32.2 kg MJ^{-1} (MJ = megajoule), respectively. When defined within common boundaries, these three relationships: energy input, energy output and yield productivity allow researchers, farmers and policy-makers to select production systems and/or practices that better manage fossil and renewable energy for food production. Current mechanized agriculture has an energy efficiency ratio of 0.9. With most energy being supplied by fossil fuels. The energy efficiency for biointensive production of onions in our study was over 50 times higher than this value (51.5) and 83% of the total energy required is renewable energy. Biointensive production offers a viable energy use alternative to current production practices and may contribute to a more sustainable food system.

Key words: biointensive, energy efficiency, organic, onion, manual production

Introduction

Modern food production shows signs of production stagnation, resource depletion and stress on the environment. To attain a sustainable food system will require increased intensification of land use, improved energy efficiency/productivity and increased use of renewable energy. The efficient utilization of energy in agriculture will lessen negative impacts on the environment[1–3], reduce demands on natural resources and increase sustainability within food production[3]. Current food production practices rely heavily on fossil energy for production. It is estimated that 13 units of fossil energy are required to produce 1 unit of food energy[4]. One strategy for improving energy utilization is to minimize machinery and rely more heavily on human labor[1,5,6].

Historically, many cultures (i.e., Chinese, Greek and Mayan) have relied on human labor and biologically intensive (biointensive) production practices. These practices have currently been developed and refined to include deep soil preparation (60 cm), close plant spacing and the utilization of on-farm produced compost crops to aid in sustaining soil fertility[7–10].

Biointensive farms are small by design. Small farms have the well-established advantage of an inverse relationship of size to productivity[11]. Also, biointensive production practices utilize deep soil (similar to sub-soil like) techniques similar in deep soil preparation which have reported yield increases of up to 63% over shallower tillage practices[12].

Biointensive production practices allow for detailed and specific on-farm data collection and review. Farm-level

Figure 1. Biointensive production of onions, Pennsylvania, USA, 2004.

data provide important and specific information for a given farm. Repeated over several farms and crop types, farm data can also support more generalized conclusions. Farm-level data provide the ability to test combinations of inputs and techniques, to judge energy efficiencies of potential combinations of inputs and to isolate the most important elements that affect energy efficiency[13].

It is important to establish commonalities in the evaluation of energy flow to minimize disparities in reporting and subsequent difficulties in comparing energy balance conclusions. One important part of this standardization is similar system boundaries[13]. System boundaries and commonalities allow researchers, farmers and policy-makers to compare energy data.

The push away from fossil energy dependence and pull toward a more sustainable food system is important for producers and society in general. Increasingly refined accounting will be needed to evaluate individual components of production. This preliminary study offers a task-oriented evaluation of human labor, with specific considerations for gender, age, weight and climate. The embodied energy of specific tools used in biointensive small-scale food production was calculated. Onions (*Allium cepa*) were the vegetable crop chosen for the study.

Materials and Methods

Location, soils and climate

This study was conducted in 2004 at Sonnewald Natural Foods, Spring Grove, York County, Pennsylvania, USA; latitude 39.8744, longitude −76.8646 and elevation 135 m (443 ft). Climatically, Spring Grove has an average winter temperature of −0.2°C (31.6°F) and an average summer temperature of 22.6°C (72.6°F), with a relative humidity of 53%. Precipitation averages 1016 mm (40 inches) of rain with 53% falling between May and October. Seasonal snow averages 802.6 mm (31.6 inches). Sunshine is available 67% of the possible time in the summer and 50% of the possible time in the winter[14].

Figure 2. Biointensive production of Alisa Craig onions (coin is 2.4 cm in diameter) Pennsylvania, USA, 2004.

The soils are part of the Manor/Mt Airy series. This is a coarse–loamy, micaceous, mesic Typic Dystrochrepts. It consists of very deep, somewhat excessively drained soils on ridge tops, side slopes and hillsides on dissected uplands. These soils formed in channery material weathered from residuum, schist and phyllite[14]. The research area had a <3% slope (westerly). Organic soil practices had been in use for 50 years. The area of specific research had been utilized for 3 years for vegetable production, prior to that it had been in sod for ~8 years. For the 3 years previous to this study, annual applications of compost (composed of municipal leaves and horse manure) were applied, resulting in a soil organic matter (SOM) content of ~5%. Weeds had been controlled for 3 years with annual cover crops, stale seed beds and weed management during cropping cycles.

Biointensive production method and related tools

Utilizing biointensive crop production principles[7,8], permanent beds and pathways, 1.5 m (5 ft) and 0.3 m (1 ft) wide, respectively, were established 3 years prior to this study. These beds ran approximately north to south. The soil had been prepared to a depth of 0.6 m (2 ft) using a double-digging hand-tillage technique[8] for 3 years prior to this study. For this production cycle, a U-bar was utilized for bed soil tillage. A U-bar is a fabricated metal broad fork (built by the author) with nine 0.5 m (19 inch) steel tines and two 1.6 m (61.5 inch) long handles. The U-bar is 74 cm (29 inches) wide, allowing two side-by-side passes to till the 1.5 m wide bed. The user stands on the tine support bar and rocks the tines into the soil. Utilizing the operator's weight, the operator leans back resulting in the upward movement of the tines through the soil, providing quick and thorough primary hand tillage. Following U-bar treatment, the bed was then raked.

Table 1. Activity levels and MJ burned per individual worker for farming/gardening tasks, with adjustment for gender.

	Farming/gardening activity			
	Very light work (1)	**Light work (2)**	**Moderate work (3)**	**Heavy work (4)**
	Seeding Watering Broadcast Seeding	Harvesting Hauling (light) Weeding (light) Raking Hoeing (light) Transplanting	U-baring (light) Hauling (heavy) Hoeing (heavy) Scything Sifting compost Turn pile	U-baring Double digging
$MJ\,kg^{-1}\,h^{-1}$				
Male	0.006	0.012	0.018	0.035
Female	0.005	0.011	0.017	0.034
$MJ\,h^{-1}\,laborer^{-1}$				
Male 86.5 kg (190 lb)	0.519	1.038	1.557	3.028
Adjusted for age 53 (10%)	0.467	0.934	1.399	2.725
Female 56.8 kg (125 lb)	0.284	0.625	0.966	1.931

Onion production

Eight onion (*A. cepa*) varieties (Alisa Craig, Grex, Super Star, Clear Dawn, New York Early, Siskiyou Sweet, Prince and Delgado) were hand sown on 15 January in wooden flats, $59 \times 36 \times 7.6\,cm^3$ ($23 \times 14 \times 3\,inch^3$). Each flat contained mesophilic compost as a growing medium. This compost was produced on the farm. Twenty rows were made along the width of the flat. Each row was approximately 1.3 cm (0.5 inch) deep. Approximately 30 seeds were planted and covered in each row. This technique yields approximately 20 plants row^{-1} and 400 plants $flat^{-1}$. At 15–20 cm (6–8 inches) in height, one-third of the onion plant tops were removed. This was repeated three times. Trimming the tops of the onions helps to create stockier transplants that are more durable and increase the survival rate. Seedlings were raised in a compost-heated high tunnel (greenhouse structure without any direct supplemental heat). No accounting of heat energy generated from the compost or the embodied energy of the high tunnel was included in this study. Plants were hardened off in early April. Transplanting was done 8–12 April on 15 cm (6 inch) offset center spacings yielding 621 plants per bed (see Figs. 1 and 2). The unit 'bed' is described as $1.5\,m \times 6.15\,m = 9.2\,m^2$ ($5\,ft \times 20\,ft = 100\,ft^2$). Three manual weed control hoeings were performed utilizing a 12 cm (5 inch) wide trapezoid hoe (Johnny's Selected Seeds, item no. 9589). Mesophilic compost (produced by author) was added at the rate of $0.15\,m^3$ ($4\,ft^3$) per bed. No additional soil amendments, insect or disease management was necessary (see Fig. 2). When the onions reached maturity, ~50% water content, the tops were laid flat with the back of the garden rake. Onions were harvested 9–14 June by hand, placed in a two-wheeled handcart and weighed. Yield data were collected at this point. The onions were cured and stored for market sales.

Assessing energy expenditure

Human labor. It is a challenge to evaluate human labor energy expenditures. One of the most accurate methods is the metabolic cost as measured by either oxygen consumption or doubly labeled water isotopes[15]. These methods are impractical for on-farm evaluations due to expense and complexity. The factorial method accounts for energy expenditures by recording the type and duration of physical activities[15]. The factorial method was utilized in this study.

Tasks performed by human labor were divided into four energy activity levels[16,17] (Table 1). These four activity levels are: very light work, light work, moderate work and heavy work (assigned numbers 1, 2, 3 and 4, respectively). Farm-related work was established within each level, based on the author's 30 years of vegetable production experience. The energy output of these activity levels was adjusted for gender, age and environmental influences (Table 1). These factors were used to establish values of $MJ\,h^{-1}$ activity level (or $task)^{-1}$ individual $worker^{-1}$.

Gender affects energy expenditure. Females utilize 7–10% less energy to perform the same task per body mass as their male counterparts[15–17]. Gender was accounted for among the specific laborers for this study.

Environmental influences have been shown to affect the amount of energy consumed per activity[15,16]. Environmental temperatures $\geqslant 37°C$ (99°F) result in increased energy requirements for human labor[17]. Research also indicates that a cold environment $\leqslant 14°C$ (57°F) can result in a 5% greater energy cost for labor[15]. In addition to temperature, altitude can make a difference in energy expenditure. This study was conducted well below 'high altitude'[15]. Daily high and low temperatures and altitude adjustments to the $MJ\,h^{-1}$ for human labor were not

Table 2. Embodied energy of tools and equipment used in biointensive onion production.

Tools	Steel (kg)	Steel embodied energy/tool (MJ kg^{-1})	Useful life of steel (years)	Steel embodied energy per year (MJ)	Lumber (kg)	Lumber embodied energy/tool (6 MJ kg^{-1})	Useful life of lumber (years)	Lumber embodied energy per year (MJ)	Total embodied energy per tool per year (MJ yr^{-1})	Tool use per bed yr^{-1} or farm yr^{-1}	Total number of times the tool is used per bed year^{-1}	MJ per bed, use or h
Cart, two wheel	27.4	848.3	30.0	28.3	15.4	92.2	15.0	6.1	34.4	1 h day^{-1}	1 h day^{-1}	0.09 MJ h^{-1}
Shovel, pointed or flat	1.1	35.2	25.0	1.4	0.7	4.1	10.0	0.4	1.8	3 h wk^{-1}	156 h yr^{-1}	0.01 MJ h^{-1}
U-bar	22.5	697.5	25.0	27.9	0.0	0.0	20.0	0.0	27.9	400 beds	80% × 500beds	0.07 MJ bed^{-1}
Rake, garden steel	0.8	24.7	25.0	1.0	0.6	3.4	10.0	0.3	1.3	3 h wk^{-1}	156 h yr^{-1}	0.01 MJ h^{-1}
Hoe, trapezoid	0.4	12.0	5.0	2.4	0.6	3.4	10.0	0.3	2.7	3 h wk^{-1}	156 h yr^{-1}	0.02 MJ h^{-1}
Flat wood	0.0				2.7	16.4	8.0	2.0	2.0	10 times yr^{-1}	10 times yr^{-1}	0.2 MJ use^{-1}

warranted as those influences were under the values for increased energy expenditures and corresponding adjustments.

The age of the laborer affects energy expenditure per task[17]. The male laborer for this study was 53 years old and required 10% less energy to perform each task[16]. The female worker was under 50 years old and required no energy expenditure adjustment.

Non-labor energy. Embodied energy was determined for each tool. Values for the embodied energy varied from 27.72 to 35 MJ kg^{-1} for steel, and from 2.8 to 18.9 MJ kg^{-1} for lumber[18,19]. For this study, the following values were used for the embodied energy of steel and lumber 31 and 6 MJ kg^{-1}, respectively[20]. Several criteria were used in determining a final value for the embodied energy in a tool; these included useful life (years), component weight of tool (kg), number of times a tool was used per year, prorated for each use and hours-of-use per bed. This information was collated and calculated in Table 2.

Irrigation utilized overhead impulse sprinklers from a tube well. Three applications of 2.5 cm (1 inches) of irrigation water (0.697 m^3 bed^{-1}) were applied at an energy cost of 0.63 MJ m^{-3},[21,22] for a total calculated energy input of 0.439 MJ bed^{-1}.

Compost was produced on site. Using biointensive techniques[7], comfrey (*Symphytum tuberosum*), corn (*Zea mays*) and alfalfa (*Medicago sativa*) were raised on 1, 2.6 and 0.85 beds, respectively. This combination totals 4.45 beds and produced 1.44 m^3 (50.7 ft^3) of cured compost. An energy flow and utilization chart (see Fig. 3) accounts for task use and expenditure of energy for the various tasks associated with compost production. Accounting was performed using an input/output analysis similar to that used for onions (see Table 3). The embodied energy of compost was calculated at 9.5 MJ m^{-3}.

Table 3, input and output energy, integrates the embodied energy of tools, irrigation, compost and labor to determine the input energy and calculates the energy ratio (output/input energy).

Based on the input and output energy (Table 3) and yield data, energy balance indicators were calculated using the following equations[22–24]:

$$\text{Energy ratio (ER)} = \frac{\text{Energy output (MJ bed}^{-1})}{\text{Energy input (MJ bed}^{-1})}, \qquad (1)$$

$$\text{Specific energy} = \frac{\text{Energy input (MJ bed}^{-1})}{\text{Onion output (kg bed}^{-1})}, \qquad (2)$$

$$\text{Energy productivity} = \frac{\text{Onion output (kg bed}^{-1})}{\text{Energy input (MJ bed}^{-1})}. \qquad (3)$$

Not all input energy expenditures were included in this study. Only anthropocentric energy inputs were used for this analysis; hence the input energy from the sun was not used in these calculations, neither was the embodied energy of onion seeds.

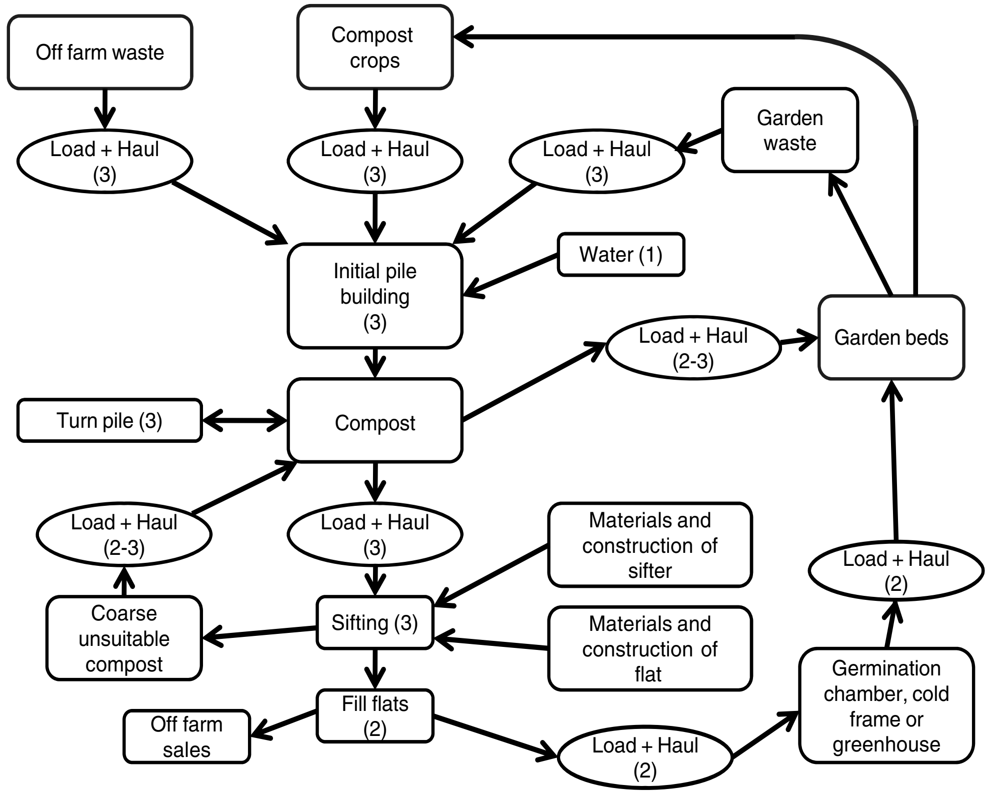

Figure 3. Flow of energy in compost production and utilization, numbers in parentheses indicate activity levels shown in Table 1.

Results and Discussion

Energy input

Human labor accounted for 3.05 MJ bed^{-1} and 62% of the total energy inputs (Table 3). Taking the average of the four activity levels for men resulted in an average energy output of 1.5 MJ h^{-1}. This is very similar to the reported general labor value of 1.58 MJ h^{-1} used by Liu[23]. Values of 2.3 MJ h^{-1} and 1.96 MJ h^{-1} have also been reported[3,24]. Norman[25] reported an energy expenditure for hoeing of 1.15 MJ h^{-1}. This is comparable to the value used for hoeing in this study for a male (53 years old, 86.5 kg) of 0.93 MJ h^{-1}. These comparisons show that the specific energy accounting used in this study was consistent with previous research work.

The input energy expenditure for compost, irrigation and the embodied energy of the tools were 1.05, 0.44 and 0.40 MJ bed^{-1}, respectively. The percent of energy expended by type of input is shown in Figure 4. Human labor and compost are primarily renewable energy and combined, contribute to a renewable energy input of 83%. No studies were found that accounted for energy balancing in hand-scale production of compost crops and subsequent compost production. For comparison, compost produced mechanically with fossil energy had an embodied energy of 1091–8817 MJ m^{-3} (adapted from Brinton[26]).

Energy output

Yield values are important considerations in energy output determination. In this study, onion yields were recorded in Table 4. The average yield was 160.2 kg bed^{-1} and that of the highest yielding variety was 205.6 kg bed^{-1}, a 348% increased yield over the US average (46.1 kg bed^{-1})[8,27] for the average onion yield and a 446% increase for the highest yielding variety. This yield is in line with other biointensive production data. Other biointensive tests have produced onion yields of 7.4 times (740%) the US average[7]. Although the study did not include onions, food production under intensive cultivation within the Biosphere II in Oracle, Arizona, showed a 216% increase in average yields over target amounts (conventional yields) for seven various legumes and starchy vegetables[9,28]. These data included a significant variation of yield over conventional production, with potato and cowpea 425% and squash and dry bean 90%. This variation over a single growing season shows both the potential in any given growing season and the possibility of crop loss and reduced yield. It should be noted that Holt and Smith[10] found no statistical difference between treatments of double digging/deep soil preparation (50 cm), single digging (25 cm) and surface cultivation (5–6 cm) in beets and bush bean yield. One difference in production techniques used by Holt and Smith and others cited was the lack of compost as an amendment.

Energy output was determined by multiplying yield values (Table 4) by the established value of 1.58 MJ kg^{-1} (172 Cal lb^{-1}) for fresh onions[29]. The resulting high yield energy output was 324.8 MJ bed^{-1} and the average energy output was 253.6 MJ bed^{-1}.

Table 3. Input–output energy for biointensively produced onions, Pennsylvania, USA, 2004.

Labor task	Laborer gender (age, kg)	Time (h)	Energy output: MJ h^{-1} (activity level)	MJ bed^{-1}
U-bar	M (53, 86.5)	0.25	1.40 (3)	0.35
Rake	M (53, 86.5)	0.17	0.93 (2)	0.16
Transplant	F (< 50, 56.8)	1.17	0.63 (2)	0.74
Hoe and weed (3 ×)	M (53, 86.5)	1.00	0.93 (2)	0.93
Compost (load, haul and spread)	M (53, 86.5)	0.25	0.93 (2)	0.23
Seeding flat	F (< 50, 56.5)	0.10	0.28 (1)	0.03
Seedling care	F (< 50, 56.5)	0.50	0.63 (2)	0.32
Harvest	F (< 50, 56.5)	0.50	0.63 (2)	0.32
			Labor sub-total	3.08
Soil amendments	**m^3 (ft^3)**		**MJ m^{-3}**	**MJ bed^{-1}**
Compost	0.11 (4)		9.5	1.05
Irrigation	**m^3**		**MJ m^{-3}**	**MJ bed^{-1}**
(3) 2.54 cm applications bed^{-1}	0.6972		0.63	0.44
Embodied energy of tools (see Table 2)				**MJ bed^{-1}**
Shovel				0.01
U-bar				0.07
Rake				0.01
Hoe				0.02
Big cart				0.09
Flat (wood)				0.20
			Tools sub-total	0.40
Input energy (MJ)				4.97
Output energy (MJ, average yield)				253.6
Energy ratio (average yield)				51.0

Table 4. Onion yield under biointensive production practices, Pennsylvania, USA, 2004.

Onion variety	Onion yield kg (lb)	Energy output MJ bed^{-1} (Cal bed^{-1})
Grex	205.6 (453.3)	324.8 (77,968)
Alisa Craig	174.7 (384.3)	276.8 (66,100)
Delgado	171.0 (376.3)	270.9 (64,724)
New York Early	160.9 (354.0)	254.9 (60,888)
Super Star	157.1 (345.6)	248.2 (59,443)
Siskiyou Sweet	155.3 (341.6)	246.1 (58,755)
Clear Dawn	149.6 (329.1)	237.0 (56,605)
Prince	107.3 (236.0)	170.0 (40,592)
Average	160.2 (352.5)	253.6 (60,630)

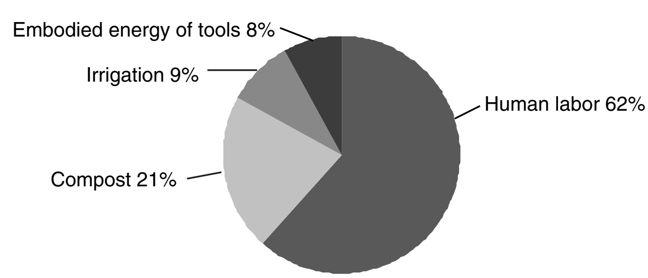

Figure 4. Input energy for biointensive onion production.

It should be noted that the total size of the planting was 20,000 onions. It is often noted that hand-scale production is primarily for subsistence. Onions, produced in these quantities offer opportunities to produce food on a small hand-scale in an efficient manner and contribute to feeding larger communities of people.

Energy balance indicators

The energy efficiency ratio (ER) was calculated using Equation 1 and found to be 51.0. No reported values for hand-scale production were found. In mechanical/fossil fuel-based production, an ER for onion production was 0.9[30]. This fossil energy based value only included input accounting for fuel and electrical energy, and excludes the embodied energy of the machinery/tools, human labor and soil amendments, whereas these are included in the biointensive production ER. Comparing these energy ratios indicates the significant energy conversion efficiency of hand-scale production, with biointensive production being 57 times more energy efficient. Hand production in general has been shown to have a high energy ratio. Reported values include 128.2 in corn production (Mexico)[31] and mixed crops including sweet potato, taro, cassava, yam and banana (New Guinea, swidden agriculture)[32]. Biointensive energy conversion efficiency, in a 3-year trial in California, was shown to have a general ER of 50 (J. Todd, personal written correspondence with John Jeavons, 2 November 1973). The specific energy as calculated from Equation 2 was 0.03 MJ kg^{-1} onions. Energy productivity was 32.4 kg onions MJ^{-1}, calculated from Equation 3. An onion energy productivity value of 1.01 kg MJ^{-1} is the only known reported value[33]. Comparing these two values, biointensive practice produced 32 times more onions (weight) per unit of input energy.

Future opportunities for sustainable energy balancing

There are three ways to improve the energy sustainability of biointensive or any production systems: lower energy inputs, increase output and increase the percent of renewable energy. The energy inputs for this study are minimized. Output/yield of onions is increased 3.5 times per unit of area in this study using biointensive techniques. Energy output might be increased further by reducing plant spacing. This reduced spacing can increase overall yield (kg and MJ) per unit of area, but typically reduces individual plant yield and size. Utilizing a greater percentage of renewable energy—for water pumping, fertilizer and amendment production, and tool manufacturing and other related processes—can also contribute to a more sustainable food production system.

Conclusion

In order to attain a sustainable food system, it is important to maximize energy efficiency and utilize renewable energy throughout the system. Increasing the detailed accounting of energy flows directly and indirectly related to a method of food production can be used to compare and improve the energy efficiencies of our current food production systems. Small-scale hand production using biointensive techniques offers decreased reliance on fossil energy and a corresponding increase of renewable energy use. Onions produced in this manner showed a very high energy efficiency and corresponding energy productivity for the season during which this study took place. These levels of productivity and efficiency are typical, based on the author's many years of experience with biointensive production. Since only one season and one crop were analyzed, this study shows that research and development of energy-efficient tools and techniques, such as biointensive production, are justified and there is strong potential to improve the sustainability of our current and future food production systems.

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