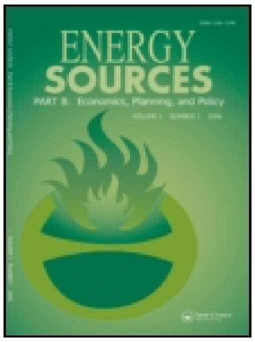

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# Energy and Water Use in Arizona Agriculture

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**Abstract** *Increasing energy and water concerns in Arizona are the driving forces to improve the efficiency of agricultural production within the state. In this article we address the energy and water uses in growing a variety of crops in Arizona. The goal of the research project is to identify and quantify all energy and water uses from the production of the initial seed, through the treatments of the soil and various chemical introductions, all the way until the crop is harvested in the field. Thus, the analysis is "from seed to the edge of the field." Using a series of secondary data sources, the article provides ranges for the energy and water consumption for the predominant crops grown in the major agriculture areas of the state.*

**Keywords** agricultural inputs, food and energy, food and water, food production

## Introduction

Increasing energy and water concerns in Arizona are the driving forces to improve the efficiency of agricultural production within the state. Real energy costs have been increasing in recent years and are likely to continue to do so in the foreseeable future, impacting the profits of the farmers and grocery store prices. The extended drought combined with unprecedented population growth in Arizona is further causing increasing concerns about water management. In this article the energy and water uses in growing a variety of crops primarily in Yuma and Maricopa counties is addressed. The goal of the research project is to identify and quantify all energy and water uses from the production of the initial seed, through the treatments of the soil and various chemical introductions, all the way until the crop is harvested and loaded for transportation in the field. Thus, the analysis is "from seed to the edge of the field." We argue that the energy and water inputs presently required in agricultural production must be fully accounted for in order to understand the best opportunities for improvement. Sustainability cannot be achieved if the current situation is not known and well understood.

Arizona has approximately 900,000 acres devoted to agricultural production. A variety of fruits, vegetables, grains, hay and cotton are grown. These crops use approximately 4.9 million acre feet of water. The amount of energy used to grow these crops has an

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approximate high range of $3.6\times10^{13}$ BTU or roughly 1,204 MW. This energy, if converted into electricity, would be the equivalent of about two Cholla Power plants operating at full capacity for one year. Alternatively this is the energy in 290,000,000 gallons of gasoline or around 38,652 tanker trucks of gasoline. The agricultural use of water and energy resources in Arizona is quite substantial (French, 2007).

An assortment of food crops were chosen for a literature study to understand the *order of magnitude* of energy and water inputs. The literature survey collected information from the United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS), university agricultural extensions, and various research groups. As will be seen, the calculations are extensive and are subject to measurement error. The amassed data can be further refined by actual field measures of crops over several seasons. However, the data reflects a reasonable range of estimates for resources used in production.

## Data Sources

The University of Arizona Cooperative Extension generated crop budgets for each county across the state.[1] These budgets use representative cropping operations derived from crop management specialists, county extension agents, and local growers. They are not a statistical sample of farms. They are estimates of costs based on materials, custom services, labor, utilities, and machinery costs derived from surveys of input suppliers. Operations vary with local conditions and farmer preference.

The crop budgets were also reviewed with a large producer to see if they were representative of their experience and operations. This large producer verified that the step-by-step operations in the specific crops we analyzed were representative of their operations. It was not possible or prudent to be more specific as detailed information by a producer is proprietary information. There is also sensitivity about water use in Arizona and legitimate concern about demand for it. The very competitive nature of farming requires producers to be selective in sharing information for public dissemination as in this article.

The information in the crop budgets was crosschecked with information from irrigation districts, water projects and the USDA Statistical Survey data.

## Methodology

The Arizona crop budgets[2] have six tables that provide information on costs of producing crops. Operations and procedures vary with local conditions and farmers' practices but in aggregate are representative of operations and represent a tremendous amount of data for life cycle analysis. Two tables were most useful: Table C—Variable Operating costs and Table E—Schedule of operations.

These tables provide the physical requirements of each operation in detail, the number of times the operation is performed, and detail of tractors and implements required. Also the machine and labor hours, required materials and inputs, required custom or hired services, and labor type needed to complete each operation are provided.

[1]See the references listed under Teegerstrom (1999 and 2001) written with various county agents. These can be accessed at http://ag.arizona.edu/pubs/ and then search for Crop Budgets.

[2]See the references listed under Teegerstrom (1999 and 2001) written with various county agents. These can be accessed at http://ag.arizona.edu/pubs/ and then search for Crop Budgets.

## Cabbage as an Example

The cabbage crop has been selected as the exemplar crop. The land preparation and growing operations are detailed in Table 1. The hours per operation per acre were estimated from the Arizona Crops Budget (Teegerstrom and Umeda, 1999). From the same source the usual numbers of preparations were estimated. In some cases, the operation was shared between two sequential crop applications (ripping and laser leveling) and thus the number of operations is listed as 0.5. The calculations are investigating the direct application of fossil fuel by the farm to the processes, so the items soil testing, packing and hauling, which are contracted to second parties, are not included. Similarly, hand thinning and hand weeding are not included as direct fossil fuel costs. In the latter case, estimates were constructed for the human application of BTUs to the process; however, the magnitudes of these processes are insignificant. The direct use of fossil fuels for irrigation is treated separately and is thus excluded from this initial analysis.

**Table 1**
Land preparation and growing operations estimates measured in the amount of diesel fuel utilized per acre for cabbage

| Month | Operation | Machine hours | Times | Diesel/hr | Diesel/acre |
|---|---|---|---|---|---|
| Aug | Rip | 0.225 | 0.5 | 16.13 | 1.81 |
| Aug | Plow | 0.45 | 1.0 | 18.33 | 8.25 |
| Aug | Disk | 0.225 | 3.0 | 19.35 | 13.06 |
| Aug | Laser Level | 0.45 | 0.5 | 15.62 | 3.52 |
| Sep | Soil fertility | 0 | 1.0 | 0 | 0.00 |
| Sep | Herbicide (ground) | 0.225 | 1.0 | 5.75 | 1.29 |
| Sep | List | 0.225 | 1.0 | 11.39 | 2.56 |
| Sep | Plant | 0.6 | 1.0 | 12.31 | 7.39 |
| Sep | Insecticide (ground) | 0.150 | 1.0 | 7.61 | 1.14 |
| Sep | Buck Rows | 0.05 | 5.0 | 5.36 | 1.21 |
| Sep | Irrigate | 0.000 | 7.0 | 0 | 0.00 |
| Sep | Disk Ends | 0.045 | 5.0 | 7.61 | 1.71 |
| Sep | Insecticide (ground) | 0.150 | 1.0 | 7.28 | 1.09 |
| Sep | Thinning | 0.000 | 1.0 | 0 | 0.00 |
| Sep | Cultivate/side dress | 0.180 | 2.0 | 15.30 | 5.51 |
| Sep | Fertilizer (ground) | 0.450 | 2.0 | 10.52 | 9.47 |
| Sep | Hand Weeding | 0.000 | 2.0 | 0 | 0.00 |
| Sep | Insecticide (ground) | 0.225 | 1.0 | 6.49 | 1.46 |
| Sep | Cultivate | 0.563 | 2.0 | 7.64 | 8.60 |
| Oct | Fertilizer (ground) | 0.450 | 2.0 | 5.75 | 5.18 |
| Nov | Insecticide (ground) | 0.225 | 1.0 | 6.49 | 1.46 |
| Dec | Harvest/field pack | 0.000 | 1.0 | 0 | 0.00 |
| Dec | Haul, custom | 0.000 | 1.0 | 0 | 0.00 |
| Dec | Disk Residue | 0.225 | 1.0 | 19.35 | 4.35 |
| Operations | Total diesel/acre | | | | 79.06 |

**Table 2**
Diesel estimates per acre of cabbage for irrigation showing both a high and low range

| | | |
|---|---|---|
| High range | 12,383,854 btu/acre | 89.09 gal/acre |
| Low range | 7,371,342 btu/acre | 53.03 gal/acre |

The estimates for the amount of diesel fuel per hour of operation were determined from the Arizona Crop Budget. The crop budget provided an estimate for the dollar cost of each operation, which was converted using per gallon cost of fuel for the county in which the crop was mostly grown. In the case of cabbage a representative conversion rate of \$0.788/gallon was used for the year of the crop budget. Different operations necessitate different configurations of machinery, so the cost per hour is not a constant and thus the amount of diesel per hour varies with the operation. It should be noted that diesel fuel costs have risen dramatically since the data were collected for the estimates; however, the cost does not impact the amount of fuel used—it simply places increased importance on energy savings.

The amount of diesel used per acre is then easily calculated by the following equation:

$$\text{Diesel/acre} = \text{Machine hours/acre} * \text{Times} * \text{Diesel/hours}. \quad (1)$$

Thus, the consumption of diesel fuel for each acre of cabbage grown is estimated at roughly 79 gallons for the operations of the various pieces of farm equipment.

Irrigation estimates were evaluated with both a high and low range. For Cabbage, Dainello (2003) estimates a total of 25 acre inches or 2.08 acre feet. The Arizona crop budget, perhaps due to increased evaporation combined with less precipitation between Texas and Arizona estimates 42 acre inches or 3.5 acre feet. Using an estimate of 1037 kWh/acre foot for the energy used in irrigation (Wateright, 2005) and a constant conversion rate of 3,412 BTU/kWh and a constant of 139,000 BTU/gallon of diesel, then Table 2 shows the estimates for the energy cost for irrigation.

Irrigation for Arizona crops uses both electricity to pump ground water and diesel pumps to pump water from the Colorado River. Cabbage is grown in Maricopa County and therefore uses ground water irrigation. To maintain the consistency, the estimates for electricity were utilized and then converted into "virtual" gallons of diesel fuel. In order to maintain a consistent unit of measure the combined gallons of diesel are used throughout the project.[3]

The energy use of *applying* the various chemicals is included in Table 1; however, the energy embodied in those chemicals has not been included yet. Using a National Agricultural Statistics Service (2005a,b) study estimates for the amount of each chemical type and the amount of coverage were determined. Nagy (1999) estimates the amount of energy embodied in each chemical. Since the former study used pounds per acre and the latter study used MJ/kg, a series of conversions were necessary to determine the energy used per acre as shown in Table 3.

Converting into diesel equivalents the high and low range for the embodied fossil fuels in the various chemicals is shown in Table 4.

[3]Beyond the scope of this paper is estimating the life-cycle energy costs of either electricity or diesel fuel.

**Table 3**
Chemical use in terms of BTU/acre for cabbage

| | Total acres, 3400 | | Energy use per kg | |
|---|---|---|---|---|
| Fertilizer | % coverage | Pounds/acre | MJ/kg | BTU/acre |
| High | | | | |
| Nitrogen | 0.96 | 182 | 75.63 | 5.92E+06 |
| Phosphorus | 0.77 | 178 | 15.8 | 1.21E+06 |
| Pesticide | 0.85 | 0.00 | 326.34 | 1.04E+06 |
| Herbicide | 0.57 | 0.00 | 252.36 | 5.23E+05 |
| Other Chemicals | 0.58 | 2.54 | 252.36 | 2.76E+05 |
| Total | | | | 8.98E+06 |
| Low | | | | |
| Nitrogen | 0.96 | 148 | 75.63 | 4.82E+06 |
| Phosphorus | 0.77 | 107 | 15.8 | 7.28E+05 |
| Pesticide | 0.85 | 1.48 | 326.34 | 2.08E+05 |
| Herbicide | 0.57 | 1.58 | 252.36 | 1.71E+05 |
| Other Chemicals | 0.58 | 0.00 | 252.36 | 0 |
| Total | | | | 5.92E+06 |

**Table 4**
Diesel estimates per acre of cabbage for chemicals showing both a high and low range

| | | |
|---|---|---|
| High range | 8,975,576 btu/acre | 64.57 gal/acre |
| Low range | 5,924,090 btu/acre | 42.62 gal/acre |

Recall that the goal of this research project is to show the total energy embodied in each crop "from seed to the edge of the field." So, estimates for the energy used in producing the necessary seeds were evaluated. Using Nagy (1999), an average embodied energy value is 20.64 MJ/kg of seeds. An estimate for the amount of cabbage seeds per pound is 126,000 (Department of Horticulture and Crop Science, 2003). A high estimate for the required seeds per acre is 156,000 (Mayberry et al., 1996) and a low value from the Arizona Crop Budget is 90,000. Thus Table 5 shows the embodied energy incorporated in the seeds used to grow the cabbage. The magnitude of these

**Table 5**
Diesel estimates per acre of cabbage seeds showing both a high and low range

| | | |
|---|---|---|
| High range | 10,986 btu/acre | 0.08 gal/acre |
| Low range | 6,338 btu/acre | 0.05 gal/acre |

**Table 6**
The embodied energy from machine operations for cabbage

| | |
|---|---|
| Acres | 3,400 |
| Total diesel | 268,807 |
| Head/acre | 10,647 |
| Diesel/head | 0.00743 |
| BTU/head | 1,032 |
| Kcal/head | 4,096 |

values is very small compared to the operation of the machines, irrigation and chemical applications.

Tables 1, 2, 4, and 5 show estimates, including high and low ranges, for the amount of diesel fuel embodied in the production of cabbage in Arizona. A total of 3,400 acres of cabbage was grown in Arizona. Table 6 shows the average embodied energy from the machine operations. The calculations are obvious.

Tables 7 and 8 show the total embodied energy from all energy applications using the high and low estimates from the previous tables.

The USDA standard for human consumption of food is 2,000 kilocalories per person per day. Using secondary data, the estimated amount of embodied fossil fuel in *a single* head of cabbage grown in Arizona is between 9,054 and 12,061 kilocalories.

**Table 7**
The high estimated total embodied energy from all fossil fuel applications for cabbage

| | |
|---|---|
| Acres | 3,400 |
| Total diesel | 791,537 |
| Head/acre | 10,647 |
| Diesel/head | 0.02187 |
| BTU/head | 3,039 |
| Kcal/head | 12,061 |

**Table 8**
The low estimated total embodied energy from all fossil fuel applications for cabbage

| | |
|---|---|
| Acres | 3,400 |
| Total diesel | 594,174 |
| Head/acre | 10,647 |
| Diesel/head | 0.01641 |
| BTU/head | 2,282 |
| Kcal/head | 9,054 |

**Table 9**
Water consumption for the cabbage crop in Arizona

| | |
|---|---|
| Acres | 3,400 |
| Acre Feet High | 3.50 |
| Acre Feet Low | 2.08 |
| Gallons/acre High | 1,140,480 |
| Gallons/acre Low | 678,857 |
| Total Gallons High | 3,877,631,898 |
| Total Gallons Low | 2,308,114,225 |
| Head/acre | 10,647 |
| Water/head High | 107 gallons |
| Water/head Low | 64 gallons |

In addition to the embodiment of directly used fossil fuels, growing cabbage also used substantial amounts of water. Using the previously mentioned ranges of 25 to 42 acre inches, Table 9 shows the water consumption needed to grow cabbage in a desert state.

The amount of water necessary to grow a typical head of cabbage is estimated to be between 64 and 107 gallons.

## Food Crop Analysis

The analysis used for the cabbage crop was also used for various other food crops grown in Arizona. Table 10 shows the direct operations machine use for the food crops. Chile peppers, onions, potatoes and watermelons are measured in pounds per acre. Spinach is

**Table 10**
Land preparation and growing operations estimates measured in the amount of diesel fuel utilized per acre for food crops in Arizona

| Crop | Acres | Diesel/acre | Head/acre | Diesel/head | BTU/head | Kcal/head |
|---|---|---|---|---|---|---|
| Broccoli | 9,900 | 142 | 9,728 | 0.0146 | 2,031 | 8,059 |
| Cabbage | 3,400 | 79 | 10,647 | 0.0074 | 1,032 | 4,096 |
| Cantaloupes | 17,700 | 76 | 12,165 | 0.0000 | 866 | 3,438 |
| Cauliflower | 4,600 | 98 | 11,460 | 0.0085 | 1,183 | 4,694 |
| Chiles Peppers | 5,400 | 50 | 6,800 | 0.0074 | 1,029 | 4,084 |
| Dry Onions | 1,600 | 72 | 36,000 | 0.0020 | 279 | 1,107 |
| Head Lettuce | 900 | 131 | 27,888 | 0.0047 | 654 | 2,596 |
| Honeydews | 2,500 | 72 | 6,488 | 0.0112 | 1,551 | 6,155 |
| Leaf Lettuce | 7,100 | 131 | 27,888 | 0.0047 | 654 | 2,596 |
| Potato | 6,200 | 227 | 29,200 | 0.0078 | 1,080 | 4,288 |
| Romaine | 17,300 | 122 | 27,888 | 0.0044 | 611 | 2,423 |
| Spinach | 6,000 | 60 | 27,888 | 0.0021 | 298 | 1,184 |
| Watermelons | 6,400 | 150 | 44,000 | 0.0034 | 475 | 1,886 |

**Table 11**
The high estimated total embodied energy from all fossil fuel applications

| Crop | Acres | Total diesel | Head/acre | Diesel/head | BTU/head | Kcal/head |
|---|---|---|---|---|---|---|
| Broccoli | 9,900 | 2,823,894 | 9,728 | 0.0293 | 4,076 | 16,173 |
| Cabbage | 3,400 | 791,537 | 10,647 | 0.0219 | 3,039 | 12,061 |
| Cantaloupes | 17,700 | 4,336,552 | 12,165 | 0.0201 | 2,799 | 11,109 |
| Cauliflower | 4,600 | 1,129,660 | 11,460 | 0.0214 | 2,979 | 11,820 |
| Chile Peppers | 5,400 | 954,899 | 6,800 | 0.0260 | 3,615 | 14,344 |
| Dry Onions | 1,600 | 388,114 | 36,000 | 0.0067 | 937 | 3,717 |
| Head Lettuce | 900 | 358,438 | 27,888 | 0.0143 | 1,985 | 7,877 |
| Honeydews | 2,500 | 491,586 | 6,488 | 0.0303 | 4,213 | 16,717 |
| Leaf Lettuce | 7,100 | 2,827,674 | 27,888 | 0.0143 | 1,985 | 7,877 |
| Potato | 6,200 | 2,978,368 | 29,200 | 0.0165 | 2,287 | 9,074 |
| Romaine | 17,300 | 5,897,631 | 27,888 | 0.0122 | 1,699 | 6,743 |
| Spinach | 6,000 | 1,017,796 | 27,888 | 0.0061 | 845 | 3,355 |
| Watermelons | 6,400 | 1,960,460 | 44,000 | 0.0070 | 968 | 3,840 |

measured in bunches of 8 to12 plants. The remaining crops are measured in single heads or fruits.[4]

Tables 11 and 12 replicate Tables 7 and 8 showing high and low estimates for all direct applications of fossil fuels for the various crops.

The total amount of diesel used to grow the collection of food crops in Arizona is estimated to utilize between 3,300 and 4,100 typical tanker trucks. These estimates only include the direct use of diesel fuel on the field. Not included are the fuels costs of transporting the fuel to Arizona, distilling and processing the fuel at the refinery or the costs of processing and transporting the food to the grocery store or restaurant.

Table 13 shows the water use for the various crops. Table 14 shows the total water estimates for all acres of all crops.

For the 90,400 acres worth of food crops grown in Arizona, the high estimate shows an average of 3.7 acre feet/acre for water use and a low estimate of 2.2 acre feet/acre.

## Discussion

Using the secondary data sets as described above results in variations between the high and low estimates of diesel and water use. Table 15 shows a comparison of these estimates.

The water estimates show substantial variations. The high estimates are based on the Arizona Crop Budgets and the low estimates come from a study compiled in Texas. The geographic differences may alone explain the variances; however, direct measurements of water use from sample farms would provide far more reliable estimates. The

[4]The specific references for the cabbage exemplar were detailed in the text. The reference list includes all the source documents for the collection of crops in this section. Specific calculations are available from the authors. The Arizona Crop Budgets are a massive collection that sometimes is bewildering as are some of the NASS reports. Specific questions should be directed to the authors.

**Table 12**
The low estimated total embodied energy from all fossil fuel applications

| Crop | Acres | Total diesel | Head/acre | Diesel/head | BTU/head | Kcal/head |
|---|---|---|---|---|---|---|
| Broccoli | 9,900 | 2,582,073 | 9,728 | 0.0268 | 3,727 | 14,788 |
| Cabbage | 3,400 | 594,174 | 10,647 | 0.0164 | 2,282 | 9,054 |
| Cantaloupes | 17,700 | 3,603,554 | 12,165 | 0.0167 | 2,326 | 9,231 |
| Cauliflower | 4,600 | 1,012,567 | 11,460 | 0.0192 | 2,670 | 10,595 |
| Chile Peppers | 5,400 | 585,251 | 6,800 | 0.0159 | 2,215 | 8,791 |
| Dry Onions | 1,600 | 301,605 | 36,000 | 0.0052 | 728 | 2,888 |
| Head Lettuce | 900 | 293,422 | 27,888 | 0.0117 | 1,625 | 6,448 |
| Honeydews | 2,500 | 397,349 | 6,488 | 0.0245 | 3,405 | 13,513 |
| Leaf Lettuce | 7,100 | 2,314,773 | 27,888 | 0.0117 | 1,625 | 6,448 |
| Potato | 6,200 | 2,304,763 | 29,200 | 0.0127 | 1,770 | 7,022 |
| Romaine | 17,300 | 5,500,610 | 27,888 | 0.0114 | 1,585 | 6,289 |
| Spinach | 6,000 | 748,221 | 27,888 | 0.0045 | 622 | 2,466 |
| Watermelons | 6,400 | 1,583,453 | 44,000 | 0.0056 | 782 | 3,102 |

extremely competitive nature of the farm industry precludes public dissemination of these data.

The variations in the diesel consumption are primarily dependent on the water variations. There are minor variations in the estimates for chemicals. However, the lack of variation is not necessarily evidence that the estimates are accurate. Again, direct

**Table 13**
Water consumption for the food crops in Arizona

| Crop | Acre feet high | Acre feet low | Total gallons high | Total gallons low | Water/head high | Water/head low |
|---|---|---|---|---|---|---|
| Broccoli | 2.83 | 1.88 | 9.1.E+09 | 6.0.E+09 | 95 | 63 |
| Cabbage | 3.50 | 2.08 | 3.9.E+09 | 2.3.E+09 | 107 | 64 |
| Cantaloupes | 3.33 | 1.67 | 1.9.E+10 | 9.6.E+09 | 89 | 45 |
| Cauliflower | 3.08 | 2.08 | 4.6.E+09 | 3.1.E+09 | 88 | 59 |
| Chiles Peppers | 4.50 | 1.82 | 7.9.E+09 | 3.2.E+09 | 216 | 87 |
| Dry Onions | 2.75 | 1.94 | 1.4.E+09 | 1.0.E+09 | 25 | 18 |
| Head Lettuce | 4.29 | 3.42 | 1.3.E+09 | 1.0.E+09 | 50 | 40 |
| Honeydews | 3.33 | 1.86 | 2.7.E+09 | 1.5.E+09 | 167 | 93 |
| Leaf Lettuce | 4.29 | 3.42 | 9.9.E+09 | 7.9.E+09 | 50 | 40 |
| Potato | 5.00 | 2.03 | 1.0.E+10 | 4.1.E+09 | 56 | 23 |
| Romaine | 4.29 | 3.42 | 2.4.E+10 | 1.9.E+10 | 50 | 40 |
| Spinach | 3.00 | 1.25 | 5.9.E+09 | 2.4.E+09 | 35 | 15 |
| Watermelons | 4.17 | 1.86 | 8.7.E+09 | 3.9.E+09 | 31 | 14 |

**Table 14**
Total water use for food crops

| Crop | Acre feet high | Acre feet low |
|---|---|---|
| Broccoli | 28,050 | 18,563 |
| Cabbage | 11,900 | 7,083 |
| Cantaloupes | 59,000 | 29,500 |
| Cauliflower | 14,183 | 9,583 |
| Chiles Peppers | 24,300 | 9,819 |
| Dry Onions | 4,400 | 3,107 |
| Head Lettuce | 3,863 | 3,075 |
| Honeydews | 8,333 | 4,638 |
| Leaf Lettuce | 30,471 | 24,258 |
| Potato | 31,000 | 12,555 |
| Romaine | 74,246 | 59,108 |
| Spinach | 18,000 | 7,500 |
| Watermelons | 26,667 | 11,872 |
| Total | 334,413 | 200,661 |

**Table 15**
Ratios between the high and low estimates for diesel and water use

| | Variations | |
|---|---|---|
| Crop | Diesel | Water |
| Broccoli | 1.09 | 1.51 |
| Cabbage | 1.33 | 1.68 |
| Cantaloupes | 1.20 | 2.00 |
| Cauliflower | 1.12 | 1.48 |
| Chiles Peppers | 1.63 | 2.47 |
| Dry Onions | 1.29 | 1.42 |
| Head Lettuce | 1.22 | 1.26 |
| Honeydews | 1.24 | 1.80 |
| Leaf Lettuce | 1.22 | 1.26 |
| Potato | 1.29 | 2.47 |
| Romaine | 1.07 | 1.26 |
| Spinach | 1.36 | 2.40 |
| Watermelons | 1.24 | 2.25 |

measurement of the operations and actual chemical applications would provide a better understanding of the farming processes in Arizona.

## Conclusions

This study has been an attempt to quantify the direct energy uses for growing food crops in Arizona. The results show substantial energy inputs are necessary to grow the crops on a per head basis. This result is primarily due to the irrigation cost of pumping water onto the crops in a desert climate. Since the amount of precipitation is extremely low in the agricultural portions of the state, this study provides an interesting baseline for studying other locations that receive varying amounts of rain. Of interest would be a second study investigating how varying rainfall amounts influence the energy uses.

In a conjoint project, the research team is investigating the energy efficiency of *actual* irrigation systems. For the current study, the irrigation estimates are most problematic. The estimates for the direct use of energy for pumping are only grossly estimated. Once a better understanding of the energy uses is available—complete with sensitivity analysis—then better estimates can be developed.

The current project has only investigated the inputs of the agricultural process. The next step in the authors' research is to evaluate the outputs of the agricultural crops. the authors are investigating the energy required to produce various calorie valued output. For example, how much energy is necessary in the field to produce a salad? What is the caloric value of that salad? Obviously, with the exception of potatoes, the crops under investigation are not typically eaten for their caloric values; rather, they are consumed for other nutritional purposes. So another step, albeit a very complex one, will be to investigate the nutritional tradeoffs between crops on a basis of their energy and water inputs.

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