

FERTILIZER CO-PRODUCTS AS AGRICULTURAL EMTERNALITIES

Quantifying Environmental Services Used in Production of Food

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Abstract

The environmental consequences of processes necessary for food production are rarely factored into crop evaluations. Byproducts created as part of an agricultural system inputs, prior to use of the main product, and without further concentration or recycle, require additional fundamental environmental services associated with eliminating their environmental impact, and fall within the food production process. Emegy was used in this evaluation to determine a more realistic sustainability picture for the food we eat and to numerically value a new set of services by suggesting the incorporation of these byproducts into emegy ratios presently incorporating only inputs actually used in the process. This study also suggests the use of emternalities both as a terminology and methodology to evaluate sustainability by using emegy to value a new set of non-traditional externalities. Integrating co-product emegy in the Florida tomato evaluation increased total flows by 28%. Florida cabbage showed an 88% increase in total emegy, oranges increased by 75% and watermelon increased by 55%. A comparison of renewable emternalities to non-renewable emternalities illustrated an emegy deficit of 6.3 E22 sej/yr to the state of Florida from gypsum co-products associated with tomato, cabbage, watermelon and orange yields in 1994. The emdollar value of services to the United States for treatment of diammonium phosphate fertilizer produced in 2000 was valued at 564 billion emdollars.

INTRODUCTION

Agribusiness is an industry dependent on manufactured chemical inputs for high yields. For every additive beneficial to productivity, there are by-products requiring extensive environmental services to render them inert. Radioactive gypsum stacks, residual pesticides and increasing nutrient loading to lakes and rivers are examples. The consequences of processes necessary for food production are rarely factored into crop evaluations except for field-scale studies looking at soil loss or nutrient leaching. This paper presents a method for incorporating a larger scale perspective into agricultural commodities, and deals with the fate of co-products.

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Economic evaluations recognize the processing cost for these additives, but not the other fundamental environmental services – neither in crop production nor in the additive manufacture. While these services are sometimes recognized as important externalities from the fertilizer process, difficulty in assessing loss or redirection of use of public commodities, such as estuaries, keeps them from being broadly internalized [internalized externality is a dollar amount that has been directly added to the cost of the final product] (Pillet 2001; Pillet 1986; Koomey et al. 1997; Jordan 1995). Further, classic definitions of externalities typically deal with output products and not the environmental support required prior to production – the long-term concentration of phosphate rock or photosynthetic energy required for phosphate mining, for example (Pillet et al. 2000). Looking at the next step in food production – the field, classic externalities might cover the loss of soil as an unvalued output, but the environmental services prior to crop production are not typically considered externalities. Consequently, wastes produced just prior to use of the intended product would not be added into the cost of food production. Even if the wastes from fertilizer processing were internalized as outflowing process externalities, this input would be passed on to agribusiness (and to the consumer) as a purchased service rather than as a renewable or non-renewable component. Using services in accounting rather than actual environmental services obscures the details needed to complete an accurate long-term carrying capacity assessment of crop production.

Emergy has been extensively used to account for environmental inputs to agriculture (Ulgiati et al. 1994, Odum et al. 1987, and many others), and allows backtracking to the environmental source and numeric valuation of each input. While direct inputs are adequately priced, the byproducts of each input are usually omitted in calculating the emergy of the next recipient of the input, despite the total cost to the larger scale hierarchy (Figure 1). Because these by-products are not used in the actual production of a fruit or vegetable (the smaller inside box in Figure 1), the value of these environmental services is not counted in their emergy ratios, despite the fact that these byproducts are unavoidable and currently unrecyclable. Multi-scale evaluations are a common systems theory practice (Odum 1994, Allen et al. 1982), and are particularly important in a process as pervasive as agriculture and its supporting industries. Shifting the system perspective beyond field production incorporates environmental services not traditionally included in economic or single crop emergy evaluations. Co-products created as part of the next system's inputs, and without further

concentration or dispersion, designate additional fundamental environmental services within the food production process. In this way, gypsum, an outflowing waste product from fertilizer production and requiring renewable environmental inputs to render harmless, becomes part of the overall food process, and its environmental requirements become part of the inputs.

The evaluation's scale also determines what components are non-renewable versus purchased. In Florida, for example, where agriculture, phosphate mining and fertilizer production often exist within a single sub-basin, phosphate rock is no longer a purchased input to the agricultural process, but rather represents a non-renewable extraction, with only a fraction of the rock retained within the resource area. In fact, if viewed from a global perspective, phosphate rock is not a purchased input, but represents a non-renewable with finite bounds of particular importance to feeding a burgeoning world population. This differentiation between non-renewable and purchased is important in assessing the sustainability of not just a watershed or the state of Florida.

In economic theory, emternalities can be viewed as the metaphorical counterpart of established economic externalities. In both cases, private ownership is unclear, and both constitute flows not rendered into currency values. However, emternalities designate unassessed **inflowing** environmental contributions instead of unpriced **outflowing** impacts of economic processes. In Figure 1, pathways A, B, C, D and E represent emternalities, while F minus H and L are externalities. Pathways F and I represent costs included in traditional economic evaluations. Another difference is that externalities are internalized according to preference-related, or user, methods, whereas emternalities are valued using emergy, a thermodynamic donor methodology. Emternalities represent social and environmental inputs translated into traditional emergy units of sej/J or sej/g, but a currency ratio of \$/sej is used instead of the inverse sej/\$. This ratio is comparable to other price ratios more familiar to economists and consumers.

Several commodities have been evaluated using this concept (Pillet 2000, Pillet et al. 2000, Pillet 1995, Pillet 1987, Pillet 1986, Pillet and Odum 1984), and the idea of using non-renewable emternalities as a deficit in agricultural evaluations has been studied at a national level (Ecosys 1999). Emternalities consider only renewable and non-renewable inputs, and the difference between the two values can be viewed as a method for assessing sustainability of a particular process. If the non-renewables are greater than the renewables, the process is not sustainable. Emternalities have a

further reaching applicability than just environmental inputs – social inequality and displacement for example. This paper, however, will focus on environmental services, and specifically those associated with fertilizer production used in production of food crops.

Processing phosphate rock into fertilizer produces gypsum, carbon monoxide, and hydrofluoric and sulfuric acid as co-products, or byproducts in traditional process terminology. The substances are produced at the same time as the desired fertilizers, and therefore have the same emergy, by definition (Odum 1996), as the fertilizer. Carbon monoxide is scrubbed during the process and is therefore accounted for in the evaluation of fertilizer (Brandt-Williams 2001). Hydrofluoric acid is recycled as feedstock to other polymer processes and directly incorporated into an end use outside of this evaluation (Klein 1996). The emergy of reclamation of mined areas is not included for two reasons. Lost productivity from high clay content overburden piles is theoretically short-term since reclamation is now required by the state. This cost is indirectly passed on to the consumer through the purchase price of fertilizer.

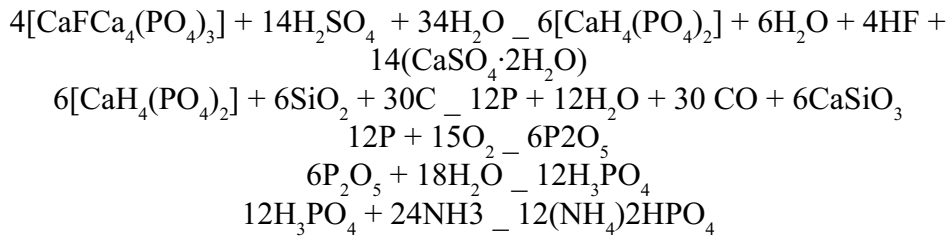
Gypsum by itself could be incorporated into other uses, but gypsum produced from Florida phosphate has high radium and radon levels (O'Brien 1997, Lloyd 1985), a radioactive material – limiting the recycle value. Large stacks of gypsum, supporting little life because of high acidity, now occupy large areas of otherwise productive land, with sulfuric acid runoff into streams and estuaries with every rain event.

Emergy is used in this study to evaluate these additional environmental services required for the food we eat and to numerically value emternalities by suggesting the inclusion of co-products created as part of the system inputs with the typical direct inputs. Emternalities are used to assess sustainability by comparing environmental fractions for renewable and non-renewable inputs. Results are presented at several different scales - field or commodity (the tomato you actually eat), regional or state (all the tomatoes eaten in the state of Florida), and national (all the tomatoes eaten in the U.S.) – to emphasize the enormity of this issue.

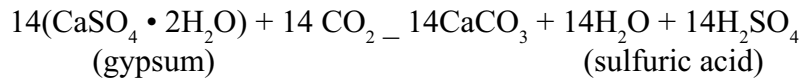
METHODS

The existence and extent of by-product formation in fertilizer production was determined from chemical equations and balances for the reactions taking place, starting with phosphate rock and ending with diammonium phosphate fertilizer (Shreve 1945). The following chemical equations illustrate the steps required to produce high-grade fertilizer from

raw mined rock. Some of these are separate reactions occurring in unit operations, but it is impossible to separate the production of gypsum and other components from the production of phosphorus in a commercial form available to photosynthesis.



In addition, standing gypsum recombines with water and atmospheric carbon dioxide to reform highly concentrated sulfuric acid.



Services required for treatment were identified using systems diagramming (Figure 2). This more detailed process diagram replaces the natural treatment process box in the larger hierarchy (Figure 1). Fertilizer production creates acidic and radioactive gypsum piles that are not useable for vegetation. As rain falls on the piles and as residual water leaches through the pile, sulfuric acid is created. This decreased pH creates an environment inhospitable to plants and some animals and dissolves the supporting limestone causing a switch action in stress levels when insufficient water is available for dilution. Gypsum's main detriment is the elimination of productivity in areas where stacks occupy what was previously pine flatwood, swamps or marsh areas and the liberation of sulfuric acid requiring dilution above a pH that will not kill plants and wildlife as it moves through the landscape and into streams and estuaries. Assumptions and sample calculations are presented for these two co-products. An evaluation of fertilizer main products is presented in Folio #4, Brandt-Williams (2001), and the emergy of this process is included in phosphate and nitrogen inputs in the original evaluation of each Florida agricultural commodity.

Gypsum Treatment Data

Productivity is assumed lost for the first 100 years of one half-life of ^{226}Ra , the main isotope present in dry gypsum (O'Brien 1997). The half-life is actually 1622 years (Summers 1975), but because the sequestering of gypsum is a political decision based on human toxicology, 100 years was

chosen as a shorter political turnover time. This assumption is not without merit for two reasons: in 100 years, if land shortage is an issue, legislation preventing recycle of radioactive gypsum in low exposure situations may be removed; in less than 100 years, areas with large phosphate deposits and high fertilizer production (typically coastal plains) may be back under seawater again; in 100 years, ecological engineering alternatives may have remediated the loss of productivity. Gross primary productivity of 8.1 J/ha/yr was used, assuming a mosaic of pine flatwood (7.3 E11 J/ha/yr, Orrell 1998), forested wetlands (7.9 E11 J/ha/yr, averaged from Odum 2000, 1.39E12 J/ha/yr from Brown et al. 2001), herbaceous wetlands (4.4 E11J/ha/yr, averaged from Odum 2000), mangroves (8.9E11J/ha/yr, from Steller et al. 1975) and saltmarsh (6.1 E11 J/ha/yr, Odum 1996) prior to gypsum stacking.

An estimated volumetric proportion of 200 feet in height for a square mile stack (Klein 1996) and a loose gypsum density of 60 lb/ft³ (averaged from 53–64 lb/ft³, Chemical Engineering Handbook 1975) were used to determine the approximate stack geometry of a typical gypsum pile. The surface area of land required for holding the specific quantity of gypsum produced during annual fertilizer production was calculated using volumetric formulas for a truncated pyramid, and using the ratio of total stack volume to the volume of gypsum produced. The ratio of gypsum to fertilizer used on a crop was determined by standard gram-mole equivalents from chemical equations presented above. The resulting surface area was used to calculate lost productivity.

Sulfuric Acid Treatment Data

A lower threshold pH of 4 is assumed as necessary for sustaining life in both terrestrial and aquatic environments (Wilson et al. 1999; D'Cruz et al. 1998; Rowe et al. 1992). The amount of water required to dilute H₂SO₄ to this pH was determined by typical molarity equations [$\log M \cdot 2 = 4$; Water g = 1 g/ml * (H₂SO₄ g * 1000 ml/l H₂O) / (M * 98 g-mole H₂SO₄) M - molarity], using an ionization potential of 2 H⁺. Loss of productivity from acid seepage is intermittent, and, because of rapid turnover times of phytoplankton and benthic organisms most adversely impacted, was assumed to be short-term. Further, since the emergy associated with this was less than 1% of the total, this component was not included in the evaluation, although at a much larger scale this might have greater impact. Loss of productivity associated with possible community switches from mangrove to saltmarsh was also not included, although with a more detailed

spatial evaluation of the extent and kind of changes, the loss could become a significant value.

Emternalities as Sustainability Indicators

Emternalities are defined as the environmental resources used in the food production system, both renewable and non-renewable. Composite emternalities add renewables and non-renewables together. A composite ratio divides the total emternalities in a commodity by the total yield to society, or $(R + N)/Y$, similar to other emergy investment ratios, and is useful in determining the percentage of environmental inputs not being accounted for in the total value to society. The renewable fraction ratio is indicative of relative chances for long-term success or suitability of a product for a particular area. The lower the ratio, the less that commodity is making use of sustainable resources, or conversely, the more services and additives are required to insure the plant outcompetes native flora and survives consumption by native fauna.

Renewables can also be designated as positive values and non-renewables as negative, where the positive designation indicates a currently unending source of energy and the negative reflects the loss to the finite amount of other environmental resources. A deficit between renewables and non-renewables indicates a need for a larger support area, and consequently a lack of regional sustainability.

RESULTS

Calculations of g-mole equivalents from the reactions producing fertilizer from phosphate rock are presented in Table 1. These values were then used to determine total co-products linked with production of specific crops, based on their respective fertilizer usage. An evaluation of tomatoes completed without co-product emergy is presented in Table 2 (from Brandt-Williams 2001). Analysis of the same crop, including gypsum and sulfuric acid co-products is presented in Table 3.

Incorporating co-product emergy in the Florida tomato evaluation increased total flows by 28%. Florida cabbage shows a 88% increase in total emergy, oranges a 75% increase, and watermelon a 55% increase.

A comparison of renewable emternalities to extracted and unavailable emternalities (Tables 4 and 5) indicates the state of Florida operates at an emergy deficit from gypsum co-products. Of the four products used in this evaluation tomatoes, with a renewable fraction ratio of 0.03, are the least suitable for Florida's long term agricultural production, while citrus,

with a renewable fraction ratio of 0.12, appears to be a better fit, and is also the commodity with the largest in-production acreage. However, the high composite ratio for all of these commodities indicates that very little of their real value is accounted for in traditional economics, since environmental services necessary for production account for 40 to 70% of their total inputs.

Calculations for phosphate fertilizer use in Algeria (Table 6) exhibit emternalities of the same order of magnitude as Florida commodities. Because water is scarce in this geographic region, both irrigation and the co-product emternalities are assumed to be essentially non-renewable, and are therefore deficits.

Total P_2O_5 production figures for both the U.S. and Algeria (Table 7) required $6.1E23$ and $2.5E20$ sej/yr, respectively, in environmental services. This service was valued at 564 billion and 224 million emdollars per year for each respective country.

DISCUSSION

For every gram of diammonium phosphate fertilizer produced, 1.5 grams of gypsum and 1 gram of sulfuric acid are produced as co-products. These specific byproducts have the potential for environmental loss and damage until transformed or diluted below a probable effects threshold. To ignore these emternalities associated with food production because they are not considered direct inputs overlooks the benefit of using emergy to evaluate the indirect costs of fertilizer inputs. While in theory the land this gypsum is stored on is in private ownership (a fertilizer company as opposed to the government of the United States), the benefits of CO_2 uptake, O_2 production and overall organic productivity belong to the public domain. It is true then that any conversion of property to unvegetated uses should be counted as an emternalities – parking garages and malls, for instance – but the growing stacks of gypsum as agribusiness feeds a growing population are perhaps a more spectacular example of loss of productivity. It is important to note, that although the gypsum stacks become storages with time, the value ascribed to them in this evaluation is the flow created during production of each gram of fertilizer used to increase agricultural yields. Adding these flows to the total emergy flow of a commodity does not violate emergy algebra. They have not been viewed from a user preference perspective, nor are they double-counted from the fertilizer emergy (see Brandt-Williams 2001 for fertilizer evaluations). Depending upon the

region and the scale of analysis, these co-products do cross boundaries as inputs and have been incorporated as such.

Current fertilizer inputs are not sustainable for the state of Florida or Algeria, as evidenced by emternalities deficits. These deficits demonstrate a high priority need for research focused on increasing gypsum utility and/or reducing fertilizer dependency either through improved field management or increased dependence on natural fertilizers. Some of the problem might be alleviated simply by imposing more stringent regulations leading to better stacking/storage of gypsum. These alternatives should be carefully evaluated using emergy.

Americans consume about 92 pounds of tomatoes a year per person, either fresh or processed (Lucier 2000). With a population of 275,562,673 (CIA 2000), this means $2.43 \text{ E}21$ sej/yr of environmental services are used to treat co-products from tomato production alone. Corn production for the U.S. requires more than $10 \text{ E}21$ sej/year for environmental treatment of fertilizer co-products (estimated from NASS 2000, Good 2000 and Herbert 1995). The emdollar value of services for these two crops alone is over 11 billion em\$/yr.

Total annual production of P_2O_5 (a fertilizer and feedstock for DAP) in the U.S. in 1998 was 12.6 billion kilograms (13,891,000 tons, McCoy 2001), and 5 million kilograms in Algeria (Algerian Agriculture Ministry). Detrimental co-products from these fertilizers require $6.1 \text{ E}23$ and $2.5 \text{ E}20$ sej/yr, respectively, in environmental services, or over 1% of the total emergy use per nation. This service was valued at 564 billion and 224 million U.S. emdollars per year for each respective country. Even the small island nation of Mauritius uses almost $4 \text{ E}17$ sej/yr to subsidize co-products from their tomato consumption despite having a per capita income of less than a third of the U.S (CIA 2000; Govinden 1999).

Although sulfuric acid and lost productivity are two large and immediate environmental hazards, there are other potential problems that should be added to a total evaluation of the modern commercial food production system. As these stacks of gypsum grow, a concentration of other trace elements, rare earth elements and fluorine occurs as particles settle and sift due to size, some of which may reach levels of environmental concern (Arocena et al. 1995). Further, while this study has focused on fertilizer impacts, production of pesticides and herbicides has associated environmental issues, and excess or poorly timed use of all three leads to other environmental impacts deserving of an emergy evaluation that goes beyond traditional transformity calculations.

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Figure 2

Energy system diagram of environmental services required to either render fertilizer co-products harmless to surrounding environment or to account for lost productivity. This box represents the “natural treatment” process contained within the system presented in Figure 1.

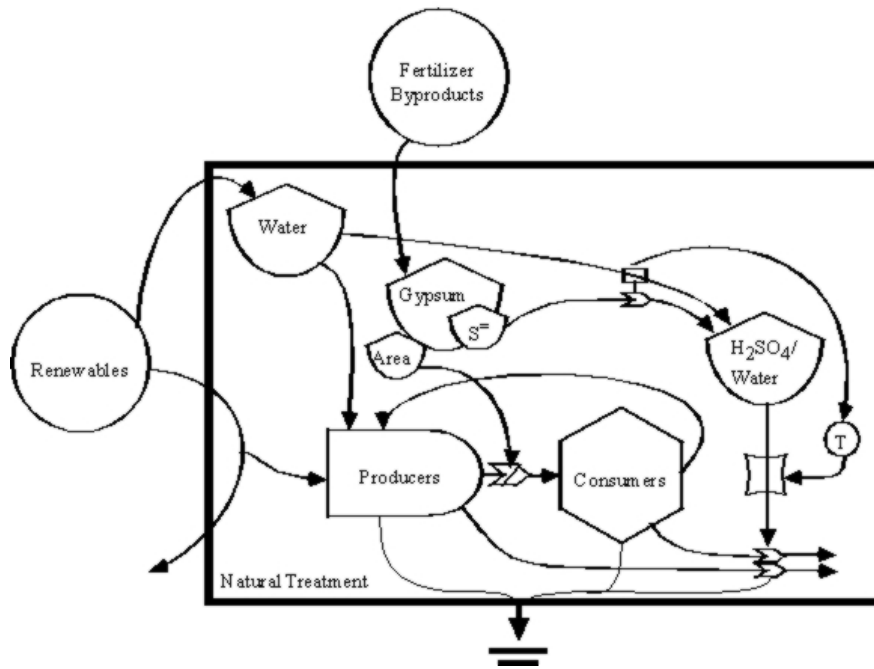


Table 1: Ratios of co-products produced during fertilizer production to fertilizer used on crops

Substance	Gram-moles produced	Ratio for DAP g used	Ratio for P g used	Ratio for N g used
DAP fertilizer	132			
Gypsum slurry	201	1.52	6.48	14.34
Sulfuric acid	98	0.74	3.16	7

Table 2: Emery evaluation of Florida tomatoes without fertilizer co-products, modified from Folio #4, Brandt-Williams (2001)

Item	Inputs Per ha/Yr	Solar Energy E13-sej/ha/Yr
Renewables		
Sun	5.93 E13 J	1
Evapotranspiration	6.02 E10 J	156
Non-renewables		
Nettopsoil loss	6.33 E7 J	<1
Purchased		
Fuel	7.37 E10 J	817
Electricity	0	0
Potash	1.39 E5 gK	26
Lime	3.29 E6 g	553
Pesticides	1.59 E5 g	401
Phosphate	4.60 E4 gP	170
Nitrogen	4.75 E4 gN	192
Labor	1.20 E9 J	16
Services	4.38 E3 \$	1199
	Total emery	3530

☐

Table 3: Emery evaluation of Florida tomatoes including environmental services for fertilizer byproducts

Item	Inputs Per ha/Yr	Solar Energy E13-sej/ha/Yr
Renewables		
Sun	5.93 E13 J	1
Evapotranspiration	6.02 E10 J	156
Non-renewables		
Nettopsoil loss	6.33 E7 J	<1
Lime	3.29 E6 g	553
Phosphate	4.60 E4 gP	170
Gypsum treatment	2.95E12*J	941
H ₂ SO ₄ treatment	2.51 E10 g H ₂ O	45
Purchased		
Fuel	7.37 E10 J	817
Electricity	0	0
Potash	1.39 E5 gK	26
Pesticides	1.59 E5 g	401
Nitrogen	4.75 E4 gN	192
Labor	1.20 E9 J	16
Services	4.38 E3 \$	1199
	Total emery	4516

☐

Table 4: Florida crops – Emortalities assessed for an individual hectare and for total state production*, then compared to total product energy

Crop	Environmental Energy		Emortality Ratios	
	EIJ gJ/ha/yr (coproduct)	EIJ gJ/FL/yr (coproduct)	Coproduct Ratio (R + N) / Y	Renewable Fraction Ratio R / Y
Tomato	13	406476	0.40	0.00
Citrus	9	1327494	0.61	0.12
Cabbage	13	36460	0.71	0.08
Watermelon	9	198333	0.33	0.08

* Average of production from 1994, Florida Statistical Abstract (Pierce 1993) and FAO/ECM data (Erick 1992).

Table 5: Emortalities categorized to show potential for sustainability

Crop	Emortalities		Energy Loss to State per Year
	Positive, Renewable EIJ gJ/ha/yr	Negative, Non-renew EIJ gJ/ha/yr	R - N
Tomato	136	1644	-3360
Citrus	168	713	-1132
Cabbage	163	1337	-442
Watermelon	140	786	-1383

Table 6: Algerian fertilizer co-products per hectare per year for selected crops, with resulting emortalities all non-renewable and therefore deficits

Crop	Irrigation water as ¹	P ₂ O ₅ application g/ha/yr	Gypsum produced	H ₂ SO ₄ produced	Emortalities g/ha/yr
Orange	3000	6.0 E5	1.7 E6	9.7 E5	9.1 E13
Almonds	3000	3.3 E5	9.9 E5	3.6 E5	3.7 E13
Figs	3000	4.0 E5	1.1 E6	6.4 E5	6.4 E13
Olive	3000	3.0 E5	8.3 E5	4.8 E5	3.0 E13

Note: data from Algeria Ministry of Agriculture

Table 7: EndoL₉₇ value for environmental services associated with annual production numbers for phosphate fertilizer (P₂O₅ is a DAP feedstock) to Algeria and the U.S.

Country	g/yr	Gypsum treatment energy g/yr	H ₂ SO ₄ treatment energy g/yr	EndoL ₉₇
Algeria	3.0 E9	2.0 E20	4.6 E19	224 exJ/ha
U.S.A.	1.3 E13	4.9 E23	1.3 E23	364 exJ/ha

Note: data from McCoy (2001) and Algeria Ministry of Agriculture. Uses 1.08 E17 gJ/g for 2000 US\$.
 * 1.08 E17 gJ/g for 2000 US\$.