Journal of Agriculture and Rural Development in the Tropics and Subtropics
Volume 110, No. 1, 2009, pages 39–47

# The Role of Bio-productivity on Bio-energy Yields

**M. J. J. Janssens**[*1], **N. Keutgen**[2] and **J. Pohlan**[3]

**Abstract**

The principal photosynthetic pathways convert solar energy differently depending on the environmental conditions and the plant morphotype. Partitioning of energy storage within crops will vary according to environmental and seasonal conditions as well. Highest energy concentration is found in terpens like latex and, to a lesser extent, in lipids. Ideally, we want plant ingredients with high energy content easily amenable to ready-to-use bio-fuel. Generally, these crops are adapted to drier areas and tend to save on eco-volume space. Competition with food crops could be avoided by fetching energy from cheap agricultural by-products or waste products such as bagasse in the sugar cane. This would in fact mean that reducing power of agricultural residues should be extracted from the biomass through non-photosynthetic processes like animal ingestion or industrial bio-fermentation. Conversion and transformation efficiencies in the production chain are illustrated for some relevant crops in the light of the maximum power theorem.

**Keywords:** photosynthesis, bio-productivity, bio-energy, energy concentration path

## 1 Photosynthesis Types

In general, photosynthesis may be considered as the process that stores light energy of the sun into carbohydrates by assimilating $CO_2$ and $H_2O$. Mineral nutrients are also required for the functioning of the photosynthetic system.

The transpiration ratio, which is the amount of water transpired per kg dry weight produced, is largest in $C_3$ plants, about one third in $C_4$ plants and remarkably low in CAM plants. The light response is saturated at half of full sunlight in $C_3$ plants, not saturated at full sunlight in $C_4$ plants and saturated already at one fourth of full sunlight in CAM plants. These special characters result in environmental preferences. $C_3$ plants dominate in temperate climate, but also occur in the tropics, while $C_4$ plants are typical of the tropics and subtropics. CAM plants, by contrast, are especially frequent in the arid tropical to Mediterranean climate. Thus, CAM plants are specifially adapted to

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[*] corresponding author

[1] Prof. Dr. Marc J. J. Janssens, University of Bonn, Institute of Crop Science and Resource Conservation (INRES), Auf dem Hügel 6, D-53121 Bonn, Germany. Email: marc.janssens@uni-bonn.de

[2] Prof. Dr. Dr. Norbert Keutgen, University of Technology and Life Sciences in Bydgoszcz, Katedra Fizjologii Roślin, Bydgoszcz, Poland

[3] Prof. Dr. Juergen Pohlan, [1]

a dry environment. However, the water deficit also limits the maximum growth rate, which ranges between 15 and 20 g per day. The maximum growth rate is maximal for $C_4$ plants and medium for $C_3$ plants.

Apart from water consumption, which is a cost-effective factor in agriculture, it is also worth focusing onto the nitrogen use efficiency, because nitrogen fertilization is also cost-effective.

In general, $C_3$ plants invest about 50% of their total soluble cell protein into Rubisco, because the affinity of this enzyme to $CO_2$ is low. $C_4$ plants with their $CO_2$ concentrating mechanism invest less nitrogen, which is 15% of their total soluble cell protein, into Rubisco. Nevertheless, we have to add another 7% of protein invested into the enzymes typical of the $C_4$ metabolism. Still, the resulting amount of nitrogen invested into the photosynthetic system is less in $C_4$ than in $C_3$ plants. To summarize, $C_4$ plants utilize significantly less protein for their photosynthetic system, resulting in a higher nitrogen use efficiency.

**Table 1:** Important physiological differences between $C_3$-, and $C_4$-plants.
Source: El Bassam (1996)

| *Component* | $C_3$-*plants* | $C_4$-*plants* |
|---|---|---|
| Apparent photosynthesis (mg $CO_2$ dm$^{-2}$ h$^{-1}$) | up to 30 | 60 – 100 |
| Light saturation (W m$^{-2}$) | up to 300 | 400 - 600 |
| $CO_2$ compensation point ($\mu$l $CO_2$ l-1) | 30 – 90;<br>temp.-sensitive | up to 10;<br>temperature-insensitive |
| Photorespiration | detectable | not detectable |
| Optimum of temperature (°C) | 10 - 25 | 30 – 45 |
| Transpiration loss (mole $H_2O$/mole $CO_2$) | 900 - 1200 | 400 - 500 |
| Daily growth rate of plants (g/m$^2$) | 34 - 39 | 50 - 54 |
| Response to $CO_2$ increase | yes | no |
| Solar conversion efficiency | 0.1 – 0.7 % | 1.5 - 2.5 % |

## 2 Energy Concentration of Plant Components

A very high energy content is stored in lipids, 38.9 kJ per gram. Non-surprisingly, lignin is also characterised by a very high energy content 26.4 kJ per gram. The energy content of proteins is not significantly lower. By contrast, the energy content of carbohydrates such as organic acids and sugars is distinctly less, about 15 kJ per gram. An exception may be the group of terpens.

Based on these data, energy plants should store energy preferably in terpens, lipids and lignin. Considering the costs related to the supply of nitrogen by fertilizers, it seems, however, ineffective to use protein crops like soybean as energy suppliers.

Terpenes are derived from the union of 5-carbon isoprene units and they are classified by the number of units.

- Monoterpenes, containing 2 isoprene units, are components of volatile essences and essential oils.
- Sesquiterpenes with 3 units are components of essential oils and phytoalexins.
- Diterpenes with 4 units represent, for example, gibberellins, resin acids, and phytol, which is the side chain of chlorophyll.
- Triterpenes with 6 units are phytosterols and brassinosteroids.
- The best known representatives of tetraterpenes with 8 isoprene units are carotenoids, while
- Polyterpenes form so-called rubber polymers.

Well-known examples of monoterpenes are pinenes, found, for example, in turpentine, limonene, also known as the smell of citrus, and eucalyptol, the smell of Eucalyptus.

With respect to energy plants, rubber-like polymers are of greatest interest, so-called polyisoprenes. Examples are:

*Hevea brasiliensis*. This rain forest tree is native to the Amazon Basin. It is the main source of natural rubber, called caoutchouc. About 90% of all natural rubber comes from the latex sap of this species.

*Palaquium gutta*. Known for its gutta-percha. It is a tropical tree, native to southeast Asia and northern Australia.

*Achras sapota*, also known as naseberry or sapodilla tree. It produces chicle, another polyterpene. This tree occurs in Central America and the West Indies.

*Mimusops balata*. Like Achras sapota, this West Indies species produces a rubber-like polymer, which differs from caoutchouc in being harder and more viscous.

*Parthenium argentatum*, called ’why-YOU-lee‘. It is a native shrub of Mexico and the southwestern United States. It contains a latex sap with polyterpenes similar to those found in Hevea rubber. It is a potentially good source of natural rubber, possibly grown on large plantations in arid desert regions. Thus, this species is a very interesting alternative, because is can be grown on areas, which are otherwise almost unsuitable for agriculture.

*Euphorbia tirucalli*. The so-called Pencil Euphorb grows well under semi-arid conditions even on marginal soils, and is widely found in Africa and in North-East Brazil. Preliminary trials were organized in Kenya with this crop by compressing biomass into briquette as a fuel wood for kitchen use in urban areas. *E. tirucalli* combines high drought and salinity tolerance with low-input requirements.

**Table 2:** Biosynthesis costs (in g glucose)
Sources: Penning de Vries *et al.* (1989); Larcher (1994)

| *Component* | *Energy content (kJ / g)* | *g glucose / g product* | *Transport g glucose / g product* | *Minimum energy costs (kJ / g product)* |
|---|---|---|---|---|
| Lipid | 38.9 | 3.030 | 0.159 | 49.4 |
| Lignin | 26.4 | 2.119 | 0.112 | 34.6 |
| Protein | 23.0 | 1.824 | 0.096 | 29.8 |
| Glycine (AA) | 8.7 | - | - | - |
| Organic acids | - | 0.906 | 0.048 | 14.8 |
| Oxalic acid | 2.9 | - | - | - |
| Malic acid | 10.0 | - | - | - |
| Pyruvic acid | 13.2 | - | - | - |
| Further Carbohydrates | - | 1.211 | 0.064 | 19.8 |
| Terpens | 46.9 | - | - | - |
| Polyglucan | 17.6 | - | - | - |
| Glucose | 15.5 | - | - | - |

AA: Amino acid; 1 Kcal = 4.186 KJ

## 3 Bio-Productivity of Selected Crops

From a practical point of view, either the entire plant should be used for the generation of energy (e.g., willow) or the harvested portion of the plant should be small in volume and, as a consequence, should contain a high concentration of ‘energy’ per volume. Examples for this latter strategy are nuts and seeds. A promising alternative may represent the strategy of generating energy by fetching energy from cheap agricultural by-products or waste products from whatever crop.

It is necessary to keep in mind that growing energy plants also requires investing energy. This energy input is the sum of energy required for seed material, nutrient supply, pesticide application, harvest, drying processes, fuel, electricity, buildings, and so on. Yet so-called Output / Input ratios can be calculated, which are the relationship of the energy yield of the main yield component divided by the energy input.

Table 3 offers an overview of the production efficiency rates of selected crops. The Output / Input ratio should, of course, be larger than 1. From a practical point of view, ratios smaller than 2 are not really attractive, which would exclude species such as Pecan, Almond, Grape wine, Sugar beet, Banana, and Apricot from our considerations. Species like Sugar cane, Sorghum, Rice, Rapeseed, Barley, Corn and Wheat, on the other hand, seem comparatively attractive.

Of course, the Output / Input ratio depends on several factors. For example, the Output / Input ratio of corn varies between 0.8 and 128 (Table 4). The latter unusually high ratio resulted from an enormous labour input by hand; however the resulting energy output per labour hour was very small. An excellent balance between the Output / Input ratio and the energy output per labour hour was achieved for corn grown in Illinois.

**Table 3:** Highest production efficiency rates of selected crops (after DIEPENBROCK *et al.*, 1995; PIMENTEL, 1980)

| *Crop* | *Country* | *Total input (MJ/ha)* | *Total output (MJ/ha)* | *Output / Input* | *MJ Output / labour hour* |
|---|---|---|---|---|---|
| Pecan ($C_3$) | Texas | 4314 | 2668 | 0.62 | 201 |
| Almond ($C_3$) | California | 57505 | 44874 | 0.78 | - |
| Grape (wine) ($C_3$) | California; irrigated | 63936 | 63943 | 1.00 | 592 |
| Sugar beet ($C_3$) | UK | 124324 | 141487 | 1.14 | 2830 |
| Banana ($C_3$) | Taiwan, South | 69761 | 95809 | 1.37 | 31 |
| Apricot ($C_3$) | California; irrigated | 26061 | 44018 | 1.69 | - |
| Soybean ($C_3$) | US, Georgia | 15247 | 28012 | 1.84 | 1286 |
| Sugar cane ($C_4$) | US, Louisiana | 40380 | 73182 | 2.18 | 2439 |
| Grapefruit ($C_3$) | US | 31628 | 93348 | 2.96 | 510 |
| Sorghum ($C_4$) | US, Texas; rainfed | 7087 | 22571 | 3.18 | 2482 |
| Rice ($C_3$) | Philippines | 11713 | 39938 | 3.41 | 49 |
| Rapeseed ($C_3$) | Germany | 22754 | 93401 | 4.10 | - |
| Barley ($C_3$) | Germany | 26319 | 117543 | 4.47 | - |
| Corn ($C_4$) | US, Illinois | 25669 | 116726 | 4.55 | 14813 |
| Wheat ($C_3$) | Germany | 28570 | 133283 | 4.66 | - |

**Table 4:** Effects of latitude and cultivation practice on energy efficiency of selected crops (after PIMENTEL, 1980)

| *Crop* | *Country* | *Total input (MJ/ha)* | *Total output (MJ/ha)* | *Output / Input* | *MJ Output / labour hour* |
|---|---|---|---|---|---|
| Banana | Hawaii | 77760 | 63849 | 0.82 | 160 |
| Banana | Australia, NSW | 81190 | 52241 | 0.64 | 87 |
| Banana | Taiwan, Central | 58477 | 55143 | 0.94 | 22 |
| Banana | Taiwan, South | 69761 | 95809 | 1.37 | 31 |
| Sugar beet | UK | 124324 | 141487 | 1.14 | 2830 |
| Sugar beet | US, California | 305159 | 214742 | 0.70 | 5765 |
| Sugar beet | US, Minnesota | 177486 | 100883 | 0.57 | 3162 |
| Sugar beet | Germany (2 horses) | 135626 | 141905 | 1.05 | 163 |
| Corn | Mexico, hand | 221 | 28319 | 128.20 | 25 |
| Corn | Mexico, oxen | 3226 | 13708 | 4.25 | 36 |
| Corn | US, California | 30209 | 106756 | 3.53 | 3411 |
| Corn | US, Texas | 145164 | 113733 | 0.78 | 4852 |
| Corn | US, Illinois | 25669 | 116726 | 4.55 | 14813 |
| Sorghum | Sudan, hand | 332 | 12357 | 37.27 | 52 |
| Sorghum | Nigeria, draft animals | 11131 | 10285 | 0.92 | 88 |
| Sorghum | US, Texas, rainfed | 7087 | 22571 | 3.18 | 2482 |
| Sorghum | US, Texas, irrigation | 46444 | 72384 | 1.56 | 3977 |

Another, interesting example is shown here for Sorghum. Once again, the Output / Input ratio was maximal when an enormous labour input by hand was invested, but the resulting energy output per labour hour was low. However, as in the case of Sorghum grown in Nigeria, a large amount of labour input does not guarantee a high Output / Input ratio.

Very interesting is also the difference between irrigated and rainfed Sorghum grown in Texas. Although the total energy output of irrigated Sorghum was much higher than under rainfed conditions, and in consequence also the resulting energy output per labour hour, the Output / Input ratio was better in case of rainfed Sorghum. It seems that a lot of experience will be required in order to optimize the cultivation systems.

What kind of energy do we like to produce? In the example given in Table 5, Miscanthus has got the much higher Output / Input ratio compared to rapeseed; however rapeseeds can easily be processed to oil, which may be used as fuel. Hence, the value of the product should also be taken into consideration.

**Table 5:** Energy efficiency of rape seed vs. Miscanthus
Source: Pude (2006)

| | *Energy efficiency comparison (kwh/ha)* | |
|---|---|---|
| *Input items* | *Rape (without straw)* | *Miscanthus (25 t dry mass/ha)* |
| Soil management, seed dressing, seed bed | 416 | 27 |
| Fertilizer | 3394 | 1062 |
| Plant protection | 504 | 32 |
| Harvesting | 157 | 1950 |
| Soil management | - | 19 |
| Transport | 98 | 959 |
| Drying | 191 | 13000 * |
| Processing to oil | 1988 | - |
| Sum Input (without processing to oil) | 4760 | 17049 |
| Sum Input (with processing to oil) | 6748 | - |
| Sum Output | 12794 | 106250 |
| Output/Input (without processing to oil) | 2.7 | 6.2 |
| Output/Input (with processing to oil) | 1.9 | - |

* if winter conditions are cold enough, drying is superfluous for Miscanthus

**Table 6:** Estimates of eco-volume and bio-volume in Mexico, Chiapas, Huixtla (average of 6 years; source: data from Toledo Toledo *et al.*, 2005 and estimates derived from Janssens, 2005).

| | *Fresh matter yield (t/ha/year)* | | | *Biometrical characteristics of sugar cane stand* | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Cane* | *Cane tops* | *Total* | *Eco-height* *d* | *Basal Area* *BA* ($m^2$/ha) | *Eco-volume* $V_{eco}$ ($m^3$/ha) | *Bio-volume* *BA * d* (*m³/ha*) | *Wesenberg* $w_b = V_{eco}/V_{bio}$ | *Crowding intensity* $C_i = 100/w$ *(%)* |
| Green cane | 125 | 18.7 | 143.7 | 2.46 | 131.0 | 24600 | 322.3 | 76.3 | 1.3 |
| Burn 1x | 96 | 14.4 | 110.4 | 2.09 | 97.5 | 20900 | 203.8 | 102.6 | 1.0 |
| Burn 2x | 89 | 13.3 | 102.3 | 1.97 | 72.3 | 19700 | 142.4 | 138.3 | 0.7 |

| | *Dry matter yield (t/ha/year)* | | | *Energy content* | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | *Yield (GJ/ha)* | | | | |
| | *Cane* | *Cane tops* | *Total* | *MJ/kg* *dry matter** | Output | Loss | $MJ/m^3$ *Eco-volume* | $MJ/m^3$ *Bio-volume* | *Gross photo-synthesis* *(t/ha/y)* |
| Green cane | 41.7 | 6.3 | 48.0 | 18.0 | 864 | 0 | 35.1 | 2681 | 192 |
| Burn 1x | 32.0 | 4.8 | 36.8 | 18.0 | 662.4 | 201.6 | 31.7 | 3250 | 147.2 |
| Burn 2x | 29.7 | 4.5 | 34.2 | 18.0 | 615.6 | 248.4 | 31.2 | 4323 | 136.8 |
| | | | | | **Maximum power law** | | | **Agricultural concentration** | **Bio-industrial concentration** |

**→ Concentration path →**

| | | | | | |
|---|---|---|---|---|---|
| Site | Atmosphere | | **Eco-volume** | **Bio-volume** | e.g. **Bio-ethanol** |
| *Active ingredient* | $CO_2$ 350 ppm | → | $(CH_2)_n$ | | $C_2H_5OH$ |
| *Energy status* | 0 $MJ/m^3$ | | $> 30$ $MJ/m^3$ | $> 2500$ $MJ/m^3$ | 22600 $MJ/m^3$ (or 1000 l) |

## 4 Efficiency of Bio-Productivity towards Bio-Energy Supply

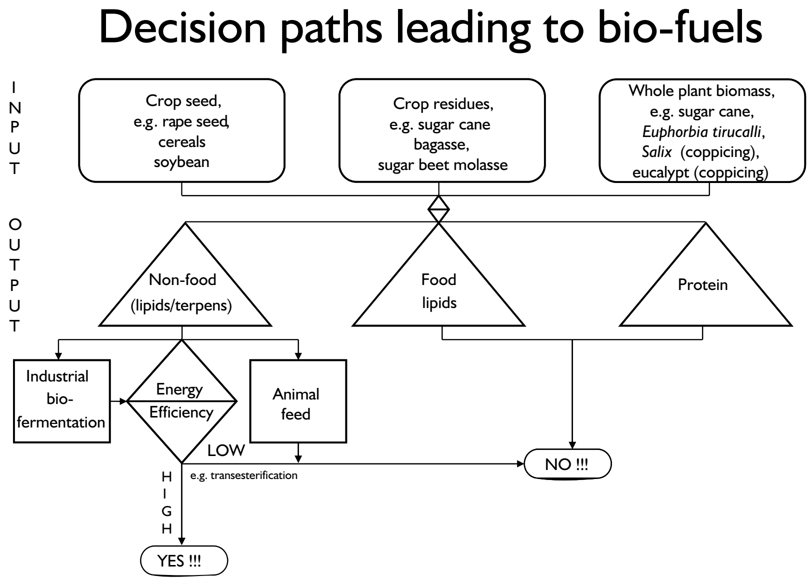
The following discussion is based on the results of a six-year case study with sugar cane in Chiapas, Mexico. A general observation in Chiapas is that after burning the size of sugar cane is reduced, which results in interesting changes of ecosystem parameters.

The fresh matter yield is reduced after burning, which results in a reduction of bio-volume (Table 6). Because the height of the stand, which is eco-height, is reduced as well, eco-volume is also smaller. Taking into account an equal energy content of 18 MJ per kg dry matter, the yield reduction results in a lower energy output. Interestingly, the energy content per eco-volume is slightly reduced, while that per bio-volume is increased by burning. In summary, agricultural practice here led to a concentration of energy, which is well in line with the concept of the maximum power law.

## 5 Concluding Remarks

The results may be summarized in a decision path leading to bio-fuels (Figure 1). Starting with crops such as rape seed, cereals, and soybean, crop residues from sugar cane or sugar beet, or whole plant biomass, for instance from sugar cane, *Euphorbia tirucalli*, Salix or eucalypt, the first question to answer is, whether it is a protein crop or, whether the product represents a food. In these cases it shall not be used for generation of energy. If the crop represents a non-food crop, in the ideal case, lipid and terpen-rich, it may be further consider as energy crops. The main question yet is the energy efficiency. If it is high, the crop may represent a valuable energy crop. If it is low, it may be considered for feeding cattle.

**Figure 1: Decision paths leading to bio-fuels**



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