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THE POTENTIAL OF CAM CROPS AS A GLOBALLY SIGNIFICANT BIOENERGY RESOURCE:

MOVING FROM FUEL OR FOOD TO FUEL AND MORE FOOD

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ABSTRACT

Bioenergy is widely seen as being in competition with food for land resources. This note examines the potential of plants that use the mode of photosynthesis known as crassulacean acid metabolism (CAM) to generate globally significant quantities of renewable electricity without displacing productive agriculture and perhaps even increasing food supply. CAM plants require of the order of 10-fold less water per unit of dry biomass produced than do common C_3 and C_4 crops, and because of their succulence are endowed with substantial water-storage capacities that helps to buffer intermittent water availability. This allows them to thrive in areas where traditional agriculture struggles, either because of low rainfall, or because the seasonality or unpredictability of rainfall is too great to allow profitable arable farming. Although as a group these plants are understudied, sufficient data are available to support estimates of the contribution they might make to global electricity supply if used as feedstock for anaerobic digestion. Two CAM species are examined here as potential bioenergy crops: *Opuntia ficus-indica* and *Euphorbia tirucalli.* Both show the high degree of drought tolerance typical of CAM plants and produce promising yields with low rainfall. Even CAM plants in semi-arid areas may have

opportunity costs in terms of lost agricultural potential, but an alternative approach to bioenergy may allow the food value of land to be increased whilst using the land for energy.

Global power generation from gas is around 5 PWh per year. The data suggests that 5 PWh of electricity per year could be generated from CAM plants cultivated on between 100 and 380 million hectares of semi-arid land, equivalent to between 4% and 15% of the potential resource.

Broader Context

Dealing with climate change is challenging. Coal and oil are energy dense fuels, the result of millions of years of accumulation and concentration of solar energy; renewables, on the other hand, rely on converting solar radiation to useful energy on a year by year basis, making them exceptionally space hungry compared to an oil field or coal mine. Bioenergy is a large potential source of renewable energy, but to make a major impact on climate change it will need extensive areas of land, with potentially serious consequences for food production and biodiversity. This paper argues, however, that the land is available provided that energy crops can be grown with levels of rainfall that are too low to support conventional arable agriculture. These potential crops can be found amongst plants adapted to semi-arid regions that use the highly water efficient mode of photosynthesis known as crassulacean acid metabolism (CAM), such as cacti and some euphorbias, and which humanity has barely begun to exploit. Not only can they produce energy but also they act as water-harvesting devices. They hold so much water that the waste water from energy conversion could be used to increase agricultural yields – especially protein. Unfortunately, as they are not part of mainstream agriculture, CAM plants have been comparatively little researched in an agronomic context and have barely been improved from their wild stock. The potential for a modest amount of R&D to increase energy supply well beyond that set out here is substantial.

INTRODUCTION

In order for bioenergy to make a real difference to global climate change, a new source of biomass is needed. However, if it must be sustainable at scale, and neither compete with food production nor make a material impact on natural ecosystems such as forests, this has to be produced on land for which there is little ecological or economic competition. The only places where such land is available in any quantity are the areas where soils are poor, and rainfall limited and or irregular. Estimates vary, but this paper argues that there may be somewhere between 2 and 5 billion ha that could theoretically be available, though undoubtedly only a modest proportion of this will be usable, for ecological or other reasons. Much of it may also have competitive use as pasture, albeit possibly of low productivity.

There is a group of plants that have evolved in these semi-arid areas and are adapted to conditions of intermittent water availability: these plants use a particular photosynthetic pathway known as crassulacean acid metabolism (CAM).

Because CAM plants are characteristic of seasonally arid environments where their productivity is severely limited by restricted water availability, CAM is often perceived as a relatively unimportant metabolic pathway compared to the better known C_3 and C_4 photosynthetic pathways found in all of our staple crop plants. Nonetheless, there may be as many as 16 000 species of plants that use the CAM pathway of photosynthesis[1], and some of these have been shown to achieve high productivities under more favourable growing conditions[2,3]. The potential that derives from their unique metabolism seems to be severely understudied or exploited.

The potential of CAM plants for bioethanol use has been identified by a number of authors[4–11], but there has been scant academic interest to date in CAM plants as feedstock for anaerobic digestion (AD) to biogas for electricity[12,13]. Nonetheless, a significant body of literature[14–18] exists that relates to the use of CAM plants, and *Opuntia* in particular, as supplementary animal fodder, and the parallels between ruminant and commercial anaerobic digestion are sufficiently strong as to allow the research done in animal nutrition to be applicable to the energy field.

Biogas has a significant advantage over ethanol as it can be produced with relatively simple technology at modest scale – compared to ethanol which needs large scale, high technology, processing plants. The fact that biogas is easily separated from water, compared to the challenges of separating ethanol from water, contributes to this simplicity.

There is likely to be only limited competition between biomass grown on semi-arid land and food production. However, one consequence of growing CAM plants is that they accumulate large quantities of water and nutrients – both of which are conserved in AD, and can be reused once digestion is completed. This leads to the possibility of growing high-value crops from the waste products of AD that would lead to an overall increase in the value of food produced from the land.

In other areas where arable farming is possible but marginal, the addition of CAM crops to a farmer's portfolio could lead to enhanced income security, and more capital deployment in agricultural infrastructure. This has the potential to increase food production several fold by improving the quality of agriculture.

WATER USE EFFICIENCY

The CAM pathway of photosynthesis enables the temporal separation of CO_2 fixation and assimilation during the day–night cycle. This allows plants to absorb CO_2 from the atmosphere during the night when air temperatures are lower – so reducing evaporative losses – and to metabolise the stored carbon during the day when solar energy is available. Although this is the defining characteristic of CAM plants, as a group they exhibit a significant degree of plasticity in their photosynthetic behaviour, and many can supplement their nocturnal CO_2 fixation with diurnal CO_2 uptake when water availability is high[4]. This flexibility makes them attractive candidates for use as energy crops in semi-arid and variable rainfall areas.

The high water-use efficiency of the CAM pathway of photosynthesis is striking[4]. CAM plants are reported to assimilate 4–10 mmol CO_2 per mol H_2O, compared to 1–2 mmol CO_2 per mol H_2O for C_4 plants, and as little as 0.5–1.5 mmol CO_2 per mol H_2O for C_3 plants. Further data on the water-use efficiency of *Opuntia* species from field studies[3] and a collation of research by the FAO[14] supports these conclusions.

It is this very high water-use efficiency under semi-arid conditions that distinguishes CAM plants as potential energy crops at a global scale. Of all the potential sources of biomass, they have the greatest land area available to them with the least competition.

CAM PLANT COMPOSITION

Few of the 16 000 or so species of CAM plants have been studied in detail, so records of their chemical composition are comparatively sparse. From an energy perspective, only one detail is really important – namely the lignin content. Lignin is well known to impair anaerobic digestion (AD), both by physically occluding more digestible material and also by adsorbing and de-activating hydrolytic enzymes[19–22], and lignin content has been shown to be the best predictor of ultimate biogas potential[23]. The low transpiration rates of CAM plants in general leads to low xylem tensions in the vascular system, and thus reduces the need for structural lignin for support on the scale seen in the massively woody stems of trees[4,5]. Nefzaoui and Ben Salem (2001) summarize the composition of several *Opuntia* species, citing lignin content in the range of 2.9% to 4.8% of dry mass[14]. Yang et al. (2015) analysed the composition of one-year-old cladodes of *O. ficus-indica*[24]. They separated the cladodes into a juice and a bagasse, and determined the lignin content of the bagasse to be 12.3 ± 1.1%; given that the juice contained slightly over 62% of the total dry matter, this equates to a total lignin content of around 4.7%. Cushman et al. (2015) also reviewed the lignin content of six leaf-succulent *Agave* species and found them to be in a similar range[25]. These low lignin levels in CAM plants should thus make them favourable as a feedstock for AD.

POSSIBLE CANDIDATE SPECIES

There are numerous species of *Opuntia* and *Euphorbia* that have yet to be investigated in any systematic way, either for their agronomy or their energy potential. For example, Lopéz-García et al.[16] list 17 species of *Opuntia* plus four varieties of *O. ficus-indica* which have been considered for animal forage in dry regions, and appear also to be suitable for AD. Likewise, Calvin[26–28] highlighted the potential of *E. lactaea* and *E. lathyrus*, but little seems to have been done to quantify their potential as energy crops[10].

Most of the historic energy interest in CAM has been for bioethanol production[4–6,9], with a particular focus on agaves. Although agaves are relatively well studied and show many favourable traits for AD, they are problematic in that they cannot be coppiced or mechanically harvested[29]. Planting, harvesting and replanting of agaves are also highly labour-intensive activities. However, if energy crops are to be grown in areas where there is little or no competition with food, then almost by definition they will be growing in areas with little or no population, and thus labour will be scarce. This trend is exacerbated by the tendency of people living in remote semi-arid areas to migrate to towns, and away from backbreaking tasks such as manual harvesting of agaves, as soon as circumstances permit. This creates challenges for the use of agave as an energy crop.

The need for a low labour input dictates a high level of harvest mechanisation. Forage harvesting is a well established agricultural technology, and forage harvesters are widely used for both agricultural crops (e.g. maize silage) and woody energy crops (e.g. willow coppice). This leads to the conclusion that a practical CAM energy crop needs to be one that can be forage harvested.

A second desirable characteristic is that the crop should coppice well. Planting from seed is expensive, and planting from cuttings or other propagules requires labour. Coppice crops, on the other hand, need no replanting. The other great benefit of coppicing is that the crop retains its roots from one cycle to the next. This maximises growth rate and the ability to harvest water, whilst minimising soil and nutrient loss – all key features in a semi-arid environment. Indeed, in addition to their superior water-use efficiency, CAM plants are also predicted to be more economical than C_3 plants in their use of nitrogen on account of their mode of photosynthetic carbon assimilation[4].

A third desirable characteristic is that the plant should have a low water content. A full economic model has been constructed of a CAM plantation providing fuel to a 2.4 MW AD plant in order to assess the sensitivity of the operation to both crop yield and moisture content (MC). Figure 1 shows the cost of harvesting and hauling per MWh of electricity generated over a range of yields and moisture contents. The data takes into account haulage distances as well as the mass of crop harvested and hauled as both yield and moisture content change. It shows that, whilst yield is slightly important, moisture content is a far more important economic characteristic. Even small increases in MC increase very significantly the mass that must be harvested and hauled to deliver a tonne of dry biomass. Many CAM plants can have MC well over 90%. The difference between 85% and 95% MC (i.e. 15% and 5% dry mass to fresh mass ratio, respectively) is a 300% increase in tonnage that must be harvested for the same potential energy yield.

Thus, the ideal CAM energy crop will be a plant that can be harvested mechanically by forage harvester, coppices well over many years, reproduces easily and rapidly, and has a low water content. .

Opuntia species

Species of *Opuntia* cacti are prime candidates for energy crops, as they are easy to propagate, coppice well, make maximal use of photosynthetically active radiation (PAR) and are easy to digest anaerobically[3,14,18,24,25,30–34]. Figure 2 illustrates the results of a trial crop propagated from single cladodes at 10 months old, in Laikipia in Northern Kenya.

There is one non-technical problem for *Opuntia* species, namely widespread perception that they are hostile invasive species outside their native habitats in the Neotropics (tropical and subtropical America). Certainly Australia[35,36] and South Africa[37,38] have faced challenges in removing them. There are many potential solutions to this issue, but the simplest may be to use spineless varieties such as *O. ficus-indica* var. *inermis*, or *O. ellisiana*. These are likely to be subject to substantial grazing pressure outside any plantation by either wild herbivores or cattle, sheep and goats – especially in semi-arid areas where they provide both food and water[39]. In addition, biological control with the *Cactoblastis* moth has proved widely successful[35].

Notwithstanding this, *Opuntia* species seem to be an attractive potential crop that could significantly increase the AD resource. There is, furthermore, significant potential for improvement across a range of key traits, and a concerted research effort into the agronomy and opportunities for improvement would be likely to pay large dividends[17].

EUPHORBIA TIRUCALLI

Another species of considerable interest for AD is *Euphorbia tirucalli* from the family Euphorbiaceae. *E. tirucalli* is an African native plant widely distributed in Africa and Asia, and used as an ornamental in many other parts of the world. Figure 3 shows *E. tirucalli* grown in Laikipia at planting density up to 20 000 plants ha^{-1}. In Africa it is used both medicinally and as a stock-proof fence. It has also been recognised as a potentially valuable source of a range of chemicals including possible liquid fuels[8,10,26,28].

Many *Euphorbia* spp. also use CAM photosynthesis in their green stems, but during periods of rainfall produce thin, deciduous leaves that utilize the standard C_3 mode of photosynthesis – enabling them to make the most of intermittent moisture availability[8].

E. tirucalli produces copious quantities of latex[40], which is recognised as an irritant and is probably mildly toxic to animals as few are known to graze it; the latex is used as a biocide and avicide in some places. Although long-term testing is needed to determine whether there are any issues with anaerobic digestion as a result of the build-up of toxic products caused by digestate cycling, some limited testing has been carried out. This shows that, in the short-term and at laboratory scale, the plant digests well[10,41] and suggests that if there are any long-term issues these may be overcome by process optimisation.

ECONOMIC POTENTIAL

Although this is an area in which further research is needed, there is sufficient data available to make preliminary estimates. The major factors that determine the economic potential of a crop for AD are the moisture content and the growth rate.

MOISTURE CONTENT

The summary of Lopéz-García et al.[16] of *Opuntia* properties is helpful in showing a consistent picture across the genus of high water content, averaging around 88% (Figure 4), but it also reveals considerable variation between species and even within species sampled by different investigators in different places and at different times. For example, *O. imbricata* dry matter content varies between 10.4% and 17.7% – itself a variation of 70%. This suggests that whilst estimates of the global economic resource can be made, local conditions and species choices will have a very large influence on actual outcomes which will be difficult to forecast.

Although the data are limited, *Euphorbia tirucalli* currently seems more promising as a biomass feedstock than *Opuntia ficus-indica*. A limited trial in Kenya reports MCs of 83%[42]; Hastilestari et al. (2013) investigated *E. tirucalli* at a range of different soil volumetric water contents (VWC) and found a range of MC of 80% to 87%[10]. The lower soil VWC corresponded to lower plant growth rates, but also materially lower MCs, so compensating somewhat for lower yield with lower harvesting and haulage costs.

Growth rate

Four published data sets provide estimates of yield as a function of rainfall for *Opuntia ficus-indica*:

- Le Houérou[39] gives an absolute minimum for rain-fed crop establishment of 200 mm in sandy soils of North Africa, except in the far West where 150 mm is possible;
- Nefzaoui and Ben Salem[14] provide estimates of fresh matter yield per hectare per year in Tunisia as a function of rainfall. In the absence of better data, the following analysis assumes the arithmetic average *O. ficus-indica* organic matter content quoted in Figure 4, namely 10.2%.
- Dubeux et al.[31] cite data from four sites in the semi-arid region of Brazil. Their data are for two planting densities – one low and the other high. The lower planting density can be disregarded because it does not reflect the potential that can be achieved with full interception of available PAR. At higher densities the annual growth rate is higher, though one might expect this to show diminishing returns once most of the PAR was intercepted.
- Nobel[43] cites a collation of data from various authors, relating to un-irrigated crops of *Opuntia*.

These four datasets are presented in Figure 5. Collating these into a single meta-data set carries some risks as it is not clear what conditions each trial or observation faced, though the implications from the literature are that the data represent unfertilised rain-fed crops. Nonetheless, the data present a coherent picture of productivity being water-limited, with a more or less linear response to water availability. The importance of this is that it demonstrates the resilience of these plants to drought – crop failure is not the issue – as there is only a proportionate decrease in productivity. Note also that these data represent observations where it is likely that field plantings were designed for manual rather than mechanised harvesting. Mechanised harvesting could well increase yields per hectare substantially by reducing the space needed for harvesting access, thus allowing greater planting densities.

de Cortázar and Nobel[44] used the Environmental Productivity Index (EPI) to forecast growth potential of *O. ficus-indica* globally. This indicated 10-year average productivity of >10 dry matter tonnes ha^{-1} yr^{-1} over 40% of the land area where minimum temperatures were greater than −10°C. Yields of 12–18 tonnes ha^{-1} yr^{-1} were typical for Africa outside the Sahara, with up to 24 tonnes ha^{-1} yr^{-1} in western South America.

In contrast to *Opuntia* species, *Euphorbia tirucalli* is not a palatable fodder crop, and so there is much less literature covering its growth and potential yield. However, there is some literature describing its potential as an energy crop. As noted earlier, Calvin[26–28] highlighted the potential of *E. tirucalli*, though he had it in mind as a source of oil rather than biogas. One possibility that should be considered is that it could be used as both a source of liquid combustibles and biogas.

In the early 1980s, Leakey carried out trials of *E. tirucalli* in a semi-arid area of Kenya. These results, which were briefly reported by deClerck and Smets[42], indicated that the crop was appropriate but it did not address issues of the economics or optimise the agronomy. They indicated that the yield could be of the order of 16–20 tonnes yr^{-1} of dry matter for plantations at densities greater than 80 000 plants per hectare.

Reliable estimates of yield as a function of rainfall are scarcer for *E. tirucalli* than for *Opuntia* spp. The only searchable data based upon field trials seem to come from the same Leakey trial quoted by Duke[40] – who cites ca. 20 inches (500 mm) of rainfall. Shao and Chu[45] quote a range of 250–1000 mm, though no yield data are included. Loke et al.[7] quote 1500 mm as the ideal rainfall, though this is clearly not relevant to the semi-arid regions for which the plant is being considered.

In an unpublished trial at Mutumayu in Laikipia, Kenya, Gasston et al. of Live Energies GmbH established test plots of *E. tirucalli* and *O. ficus-indica* in June 2012[46]. The plots were un-irrigated, and the area receives 500–600 mm rainfall annually. Growth data for different planting densities from this trial, quoted as fresh tonnes, are shown in Table 1. Taking 10% dry organic matter as an estimate, based upon the average for O. *ficus-indica* calculated previously, suggests biomass growth rates in the region of 40 tonnes dry matter ha^{-1} yr^{-1}. Whilst there is not sufficient data here to establish reliable quantitative results over time, this illustrates clearly the significant advantage of high planting densities.

These data are comparable to experimental yields quoted by Nobel[2] of 43 tonnes ha^{-1} yr^{-1} and reinforce the observation that CAM plants can be as productive as more conventional C_3 and C_4 crops under conditions of much lower water availability.

GAS YIELDS

There is limited published literature about the biogas yields from CAM plants in AD. For crops that are digestible by ruminants, given that the basic processes of AD and ruminant digestion are closely related, and because biomass creates more or less the same amount of methane per unit of digestible material, knowing how much organic matter is present in the feedstock provides a proxy for relative productivity. *Opuntia* is frequently used for forage in N.E. Brazil, where something like 400 000 ha are in cultivation[31], and in other areas of the world[15,30,34,39,47,48]. Gasston's unpublished trial[46] shows rapid digestion and good gas yields for *O. ficus-indica.* Gas yields of around 325 l kg^{-1} (Figure 6) are consistent with gas yields from other forage biomass types. For comparison, maize grown as an energy crop produces around 300–375 litres CH_4 per kg organic dry matter[49].

E. tirucalli is not used as forage, and so biomass alone cannot be used as a guide to gas yield. Extracts are reportedly toxic to some mammals and birds and an antibiotic[40], which creates some concern for its ability to be digested in an AD plant that relies on a thriving micro-biome.

Nonetheless, three groups have tested its biogas potential[10,13,41] and not reported any toxicity issues. Further long-term testing is needed to confirm this conclusion.

Hastilestari et al.[10] tested a range of different provenances of *E. tirucalli* for methane yield under AD (Table 2). The four-fold variability in these data is uncharacteristic of gas yields from other crops, and suggests either a methodological flaw, or perhaps the influence of inhibition by toxins. However, the high yield in the Kenyan trial suggests that careful selection of cultivars and optimisation of the AD process to match the feedstock should allow yields of at least this magnitude to be achievable.

Digestibility tests on samples from the Mutumayu trials were performed at the University of Hohenheim[46]. Unpublished results from this work are shown in Figure 6. The *E. tirucalli* data shows somewhat lower methane yields than either *O. ficus-indica* or the tests by Hastilestari et al.[10].

FUEL OR FOOD

No consideration of bioenergy would be complete without considering the alternative uses to which the land may be put. Although semi-arid land has limited economic value, nonetheless there is always some opportunity cost associated with a change of use. Frequently this use is low-productivity pastoralism or ranching. A key feature of the use of CAM plants on semi-arid lands, however, is the possibility that they might increase food production as a consequence of bioenergy farming, rather than reducing it.

The digestate that is left over after AD in commercial plants is generally separated into a liquid and solid stream. The solid digestate has potential as a fertiliser, but it is the liquid digestate that may offer the potential for transforming semi-arid agriculture. All plants not only collect carbon but also water and nutrients. Because of the high water content of CAM crops, harvesting and gathering the crops for energy would result in large quantities of water, in particular, being collected. In effect, the crops act as standing water-storage capacitors, capable of scavenging and retaining water from whatever rainfall is available.

Some of the water fed into an AD plant is used in the chemistry, some is lost by evaporation, but the bulk of the water input with the feedstock into an AD plant reports to the outlet of the plant as liquid digestate. It contains most of the soluble inorganics that derived from the biomass, together with a proportion of the indigestible solids that form a colloid and thus is not separated out with the solid fraction[50].

Consider a crop that produces 10 tonnes of dry matter per year per hectare at 90% moisture. Consumption by the AD process, calculated using the Buswell Equation[51], of about 13% by weight of the dry matter will leave around 89 tonnes of nutrient-rich water per hectare per year. This is equivalent to almost 9 mm of rainfall, delivered in equal amounts continuously through the year.

Collecting and using water by this mechanism contrasts with irrigation from collecting surface run-off. Collecting water in dams is only possible if there is adequate surface run-off. This requires topographical relief, soils that do not absorb all the moisture, and low evaporation rates, whereas collecting water via CAM plants requires none of these. Thus, the two approaches are complementary, and could even be implemented in the same locale.

The semi-arid areas where CAM plants could be grown as energy crops will benefit from year round sunlight, and if the biogas is used to generate electricity, exhaust gases with elevated CO_2 will also be available. These, coupled with nutrient-rich liquid available, offer the ideal ingredients for the development of highly productive agriculture using hydroponics or drip irrigation.

A recent study in the Proceedings of the National Academy of Science[52] quotes wheat under drip irrigation needing 1.4 ft (427 mm) of water, and giving yields of 115 cwt/acre (14.5 metric tonnes/hectare). Thus, 9 mm of rainfall recovered from the feedstock area would allow about 2% of the land area to be used for wheat. CO_2 fertilisation might reduce water needs even further. In practice, much higher value crops may be grown than wheat. The nutrient-rich liquid waste could find other uses however, either before being used for irrigation, or instead of such use. Growing algae is one possibility, but perhaps even more promising is the growth of highly productive Lemnaceae.

Lemnaceae are small, free-floating aquatic plants that are the subject of considerable interest as a source of protein[53–56]. They have prodigious growth rates, with doubling times of between 16 hours and 4 days[54] and can contain 25%-40% of their dry mass as protein, with the higher figures associated with the faster harvesting rates[56]. These protein concentrations are as high as soybeans, which command a market price of around US$400/tonne, and the material is highly palatable for both ruminants[57] and fish[53–55,58].

The global market for fish is large, and with pressures on natural stocks and a growing global population seeking more protein-rich diets, AD byproducts could be an important new and sustainable source of protein. Global traded production of *Tilapia* alone today is in excess of 4.5 million tonnes per year. The Chinese market price is around $1.45/kg, valuing the global market at $6.5 billion a year[59].

A further benefit to farmers of CAM plants is their resilience in the face of unreliable rainfall. In much of the world it is the unreliability of highly seasonal rainfall rather than the lack of average rainfall that constrains farming[60], and the availability of increased capital and security in such areas could substantially increase food productivity[61] with a doubling, or even quadrupling of productivity possible. Whilst for such farmers the use of conventional agricultural waste for energy generation might provide welcome additional income, the variability of this will directly correlate with rainfall and crop yields. However, a mix of CAM and conventional crops would allow biomass availability to be evened out across seasons and years, thus providing both income and security. This could be a catalyst to the investment needed to increase agricultural productivity.

GLOBAL LAND AVAILABILITY AND GENERATION POTENTIAL

Estimates of the global availability of semi-arid land where CAM crops could be grown without significant competition from agriculture are variable.

The Food and Agricultural Organisation of the United Nations (FAO) estimate 12.2% (1.8 billion ha) of the world's land area to be semi-arid[62]. They define this as 300–800 mm rainfall if the rains are summer rains, and 200–500 mm rainfall if winter rains. Davis et al.[5] cite a figure of 18% (2.7 billion ha). Kline et al.[63] highlight FAO estimates of idle crop lands ranging from 0.52 to

4.9 billion hectares. Adding together the estimated semi-arid land area as defined by FAO and the lowest of the estimates for idle crop lands, as representing potential sub-humid lands available, would suggest a global estimate of 2.3 billion hectares of land possibly available for CAM energy crops, but a range anywhere between 2 and 5 billion hectares is plausible (cf. Owen 2015)[64]. Alexandratos and Bruinsma[65], using data from the FAO Global Agro-ecological Zones Study, estimated 2.9 billion ha of land to be marginal, or very marginal, for rain-fed agriculture, of which 220 million hectares is in use for rain-fed crops. For the purposes of this analysis a nominal figure of 2.5 billion hectares is assumed.

Of this 2.5 billion ha, much will be unusable for a range of reasons. Terrain and accessibility to power evacuation infrastructure are two key factors. A third is the need to preserve ecosystems.

Clearly, in an ideal world, there would be no loss of ecosystems, but that would leave no room for human activity and welfare. The UN Convention on Biological Diversity seeks to address this through targets for land to be set aside for conservation. The Convention established the Aichi Biodiversity Targets[66] which are to be translated into national action plans for the 193 signatory countries to the convention. Target 11 seeks to ensure that at least 17% of land area should be set aside for conservation by 2020. Whilst this establishes a minimum area to be set aside it does not determine a maximum, or optimum to be set aside, or seek to influence further the inevitable social debate about the proper amount that should be used for agricultural or industrial purposes. It is also important to recognise in this debate that there is very little truly pristine wilderness left[67]. Kareiva et al. (2007) prefer to frame the conservation debate in terms of "*a discussion of what trade-offs we are willing to accept as a result of the domestication of nature*". Furthermore, it is likely that most of the land that would be most suitable for CAM energy crops is already grazed, or even over-grazed, by pastoralism and ranching.

One approach to this question is to ask how much land would be needed for energy crops to make a material contribution to global greenhouse gas emissions reduction, and then consider whether this was an acceptable trade-off. Table 3 sets out a synopsis of the calculations of energy generation potential of CAM plants. It considers a range of forecasts for growth rates, using the Laikipia gas yields from Table 1. In the interests of conservatism, it does not include the higher gas yields from Hastilestari et al. (2013)[10] for the Kenyan provenance of *E. tirucalli*.

A recent analysis of the availability of land for energy crops was carried for eight sub-Saharan African countries[68]. The analysis considered all agriculturally suitable semi-arid and arid land, and excluded all land with competing uses, including pastoral land and land where agriculture existed but was either marginal or could be enhanced by energy crops. Nonetheless, it demonstrated that approximately 10% of the total semi-arid and arid land was available for energy crops.

Coal is the world's biggest source of electricity, with approximately 9 PWh generated in 2011. The second biggest source of power was gas, at almost 5 PWh[69]. To achieve 5 PWh from CAM plants would require somewhere between 4% and 15% of the 2.5 billion hectares of potentially available semi-arid land, depending on the yield and gas production assumptions used.

The potential exists to be somewhere at the lower end of this range of land requirement if the Leakey trial data on growth rates are confirmed, and the Hastilestari et al. (2013)[10] data on gas yields are supportable with long-term testing. Furthermore, there may be considerable opportunities to improve both growth and gas yield as understanding of the agronomy and variability of the estimated 16 000 species of CAM plants improves.

Thus, there are reasonable grounds for optimism that a substantial reduction in greenhouse gas emissions, and with that a substantial reduction in the risk of catastrophic climate change, might be achieved with only a modest loss of semi-arid habitat and no loss of food production. Food production may even be increased as a consequence.

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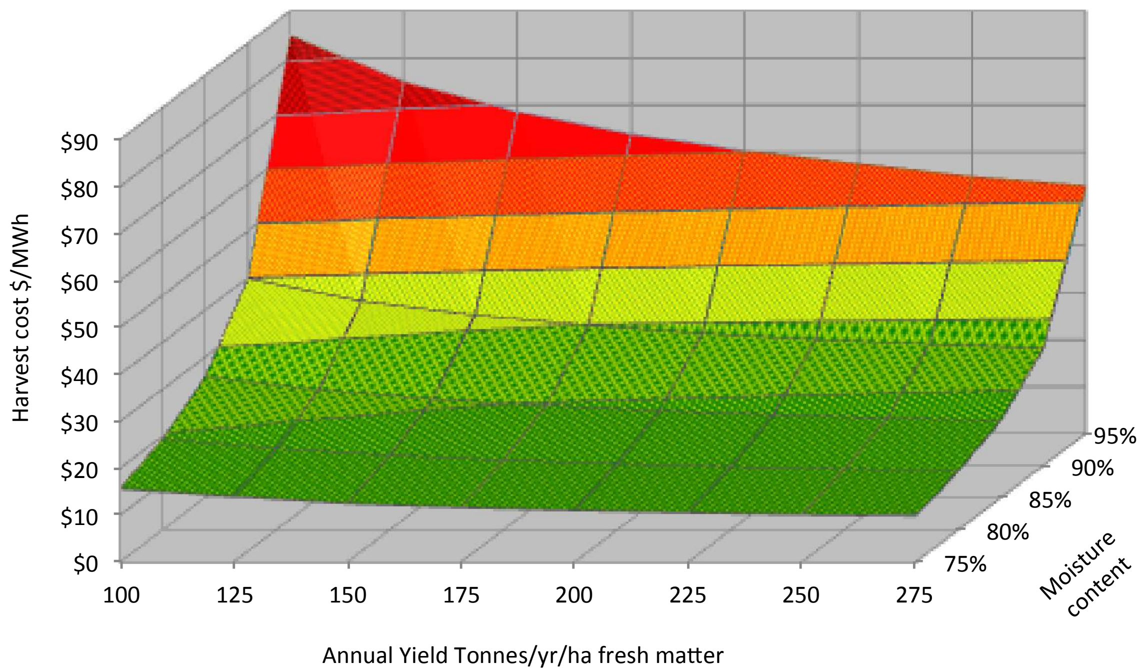

Figure 1 Modelled costs of harvesting and hauling a CAM crop for a 2.4 MW(e) AD plant based on actual costs of harvesting and hauling.

Figure 2 - Ten-month-old *Opuntia ficus-indica* in Laikipia, Kenya (photo credit George Francis).

Figure 3 - *Euphorbia tirucalli* under test in Laikipia, Kenya (photo credit George Francis).

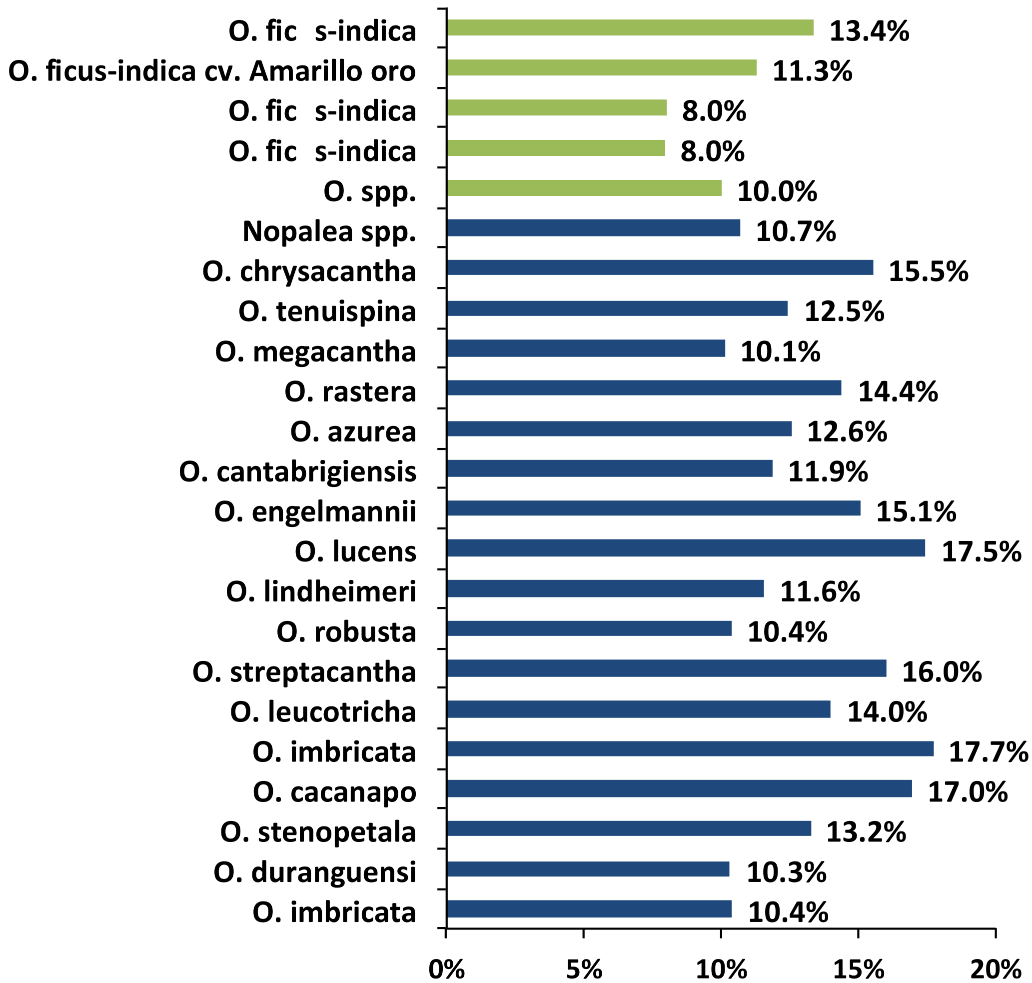

Figure 4 – Dry matter content from a range of *Opuntia* studies adapted from FAO [16]

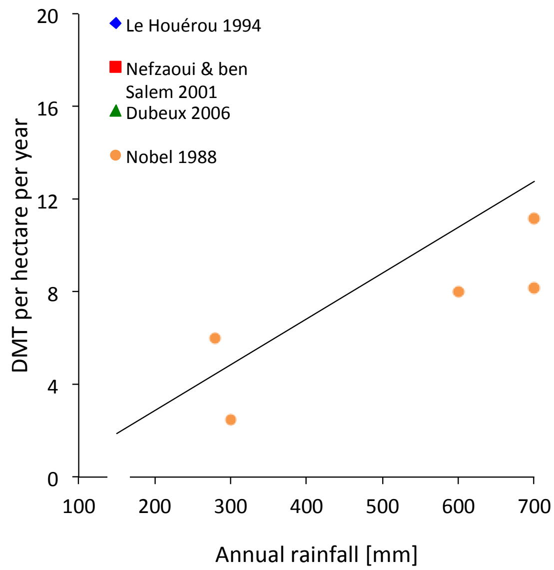

Figure 5 – Growth of *Opuntia ficus-indica* as a function of rainfall.

Plants per ha	Mass per plant (kg)	Approx. fresh biomass (tonne ha^{-1})
Opuntia, Sampled 17 months after planting		
3,333	11.0	37
8,000	10.5	84
20,000	33.0	660
Euphorbia, Sampled 12 months after planting		
66,667	1.5	100
133,333	1.0	133
266,667	1.5	400

Table 1 - Experimental biomass yields from a growth trail in Mutumayu[46]

	CH_4 yield (l/dry kg)
Togo	79
USA	161
Morocco	187
Senegal	238
Rwanda	214
Kenya	318

Table 2 – Specific methane production from *Euphorbia tirucalli* grown in different locations, adapted from Hastilestari et al. [10]

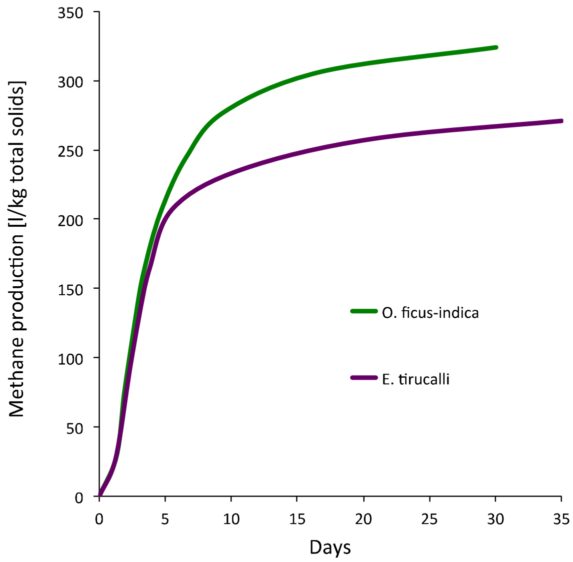

Figure 6 - Digestion rate of *Opuntia ficus-indica* and *Euphorbia tirucalli* grown in Laikipia, Kenya[46]

Electricity yields	*Opuntia* (low)	*Opuntia* (likely)	*Opuntia* (Mutumayu)	*E. tirucalli* (Leakey)	*E. tirucalli* (Mutumayu)
Dry tonnes yr^{-1} ha^{-1}	10	12	40	20	40
Gas yield (CH_4 l kg^{-1})	325	325	325	260	260
Energy in biomethane (GJ dmt^{-1})	11.59	11.59	11.59	9.28	9.28
Efficiency of AD process	64%	64%	64%	52%	52%
Electricity from biomass (MWh dmt^{-1})	1.33	1.33	1.33	1.06	1.06
Overall efficiency biomass to power	27%	27%	27%	21%	21%
Gross thermal power (W m^{-2})	0.57	0.68	2.28	1.14	2.28
Net electrical power (W m^{-2})	0.15	0.18	0.61	0.24	0.49
Total PWh at 100% of land use	33.3	39.9	133.0	53.2	106.4
Ha needed to produce 5 PWh yr^{-1}	**3.8E+08**	**3.1E+08**	**9.4E+07**	**2.3E+08**	**1.2E+08**
Proportion of available land to produce 5 PWh yr^{-1}	**15%**	**13%**	**4%**	**9%**	**5%**

Table 3 - Energy generation potential from AD using CAM crops as feedstock. Constants and assumptions used to calculate values are available in Table 1 of ESI.

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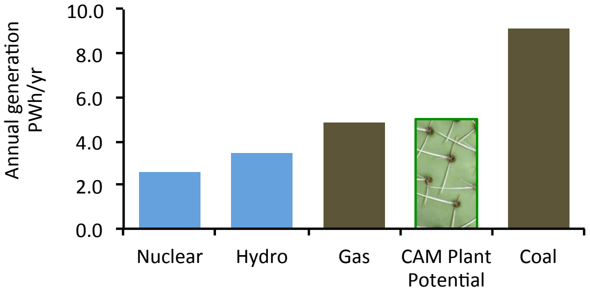
Graphical abstract



4 – 15% of the 2.5 bn ha. of semi-arid land globally could generate 5PWh/year of electricity without reducing food production, enough to make a major difference to global GHG emissions. The key is anaerobic digestion of a class of understudied, under-developed and hyper-water-efficient plants that use the crassulacean acid metabolism.