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Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes

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ABSTRACT

The need for new sources of renewable energies and the rising price of fossil fuels have induced the hope that agricultural crops may be a source of renewable energy for the future. We question in this paper the best strategies to convert solar radiation into both energy and food. The intrinsic efficiency of the photosynthetic process is quite low (around 3%) while commercially available monocristalline solar photovoltaic (PV) panels have an average yield of 15%. Therefore huge arrays of solar panels are now envisaged. Solar plants using PV panels will therefore compete with agriculture for land. In this paper, we suggest that a combination of solar panels and food crops on the same land unit may maximise the land use. We suggest to call this an agrivoltaic system. We used Land Equivalent Ratios to compare conventional options (separation of agriculture and energy harvesting) and two agrivoltaic systems with different densities of PV panels. We modelled the light transmission at the crop level by an array of solar panels and used a crop model to predict the productivity of the partially shaded crops. These preliminary results indicate that agrivoltaic systems may be very efficient: a 35–73% increase of global land productivity was predicted for the two densities of PV panels. Facilitation mechanisms similar to those evidenced in agroforestry systems may explain the advantage of such mixed systems. New solar plants may therefore combine electricity production with food production, especially in countries where cropping land is scarce. There is a need to validate the hypotheses included in our models and provide a proof of the concept by monitoring prototypes of agrivoltaic systems.

1. Introduction

Energy from biomass is claimed as being a possible substitute to fossil fuels for the future [1]. Biofuels are currently playing an increasing role in several countries such as Brazil or the USA. However, the land area that would be necessary for replacing fossil fuels with biofuels largely exceeds the cropland area of the planet. To move the 40 million cars of France only, about 40 million hectares of cereals (ethanol pathway) or oil crops (transesterification pathway) would be required, which is more than the actual cropped land area. Moreover, fuel markets of developed countries may compete with food markets of less developed countries and induce food shortages [2]. This was already observed in Mexico in 2008 when corn prices raised due to demand of the USA market for ethanol. Concerns over the impact of energy crops on the food availability are therefore shared worldwide [3]. Second generation energy crops will not change much the issue: although the yield of conversion from biomass to energy may be increased by 50% by new pathways of cracking the whole plant to energy, the needs for energy are so huge that the pressure on cropland will remain very high. Land constraints were not considered significant 10 years ago [4] because of the predicted surpluses in land and food in Europe, but the scene has changed since then [5].

Fossil fuels (petrol, gas, coal) are basically biofuels originating in the photosynthetic process, exactly as modern biofuels from biomass are. But fossil fuels result from the stockpiling of photosynthetic production for millions of years. The low efficiency of the photosynthetic process will not be able to cope with our current energy needs. The intrinsic efficiency of the photosynthetic process is quite low (around 3%) [6,7] and will remain the same with second generation energy crops.

Liquid biofuels target transportation needs. However, burning high quality molecules with a food value is questionable. With the best up to date technology, a hectare of cereals in Europe may allow a car to run for about 18000 km [8]. The transesterification pathway is more efficient (about 22 000 km). But the solar electricity pathway (solar panels producing electricity used to move electric cars) has an astonishing performance: about 3 250 000 km with

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a single hectare of solar panels on trackers, 147 times more than the transesterification pathway [8]. This is explained by the efficiency of solar panels combined with the efficiency of electric engines.

On the long term, it may therefore be questioned what the best option for producing energy from solar radiation is. Is it with liquid biofuels from cultivated crops or trees? Is it with electricity from solar photovoltaic (PV) plants? Commercial solar photovoltaic panels (PVPs) have today an average yield of 15% (monocrystalline PVPs, which are the most widely used). The latest releases in PVPs technology allow to reach 19% (monocrystalline with back contact modules, SunPower E19, SunPower, San Jose, California, USA). They are much more efficient for energy production than energy crops.

As we need both fuels and food, any optimisation of land use should consider the two types of products simultaneously. We intend here to compare two options for producing both fuels and food from a given land area:

1. Split the land area in two parts, one devoted to food production and the other to fuel production. This may be considered as the current dominant scheme of production separation [9].
2. Combine fuel and food production on the same land unit. We will explore this option in the case of mixing solar panels and food crops, as already suggested by [10]. Surprisingly, the idea of mixing solar panels and food crops was never explored since this premonitory paper. Some authors have explored the possibility to mix food and fuel production on the same land area by mixing crops for food and trees for fuel [11–13].

In this paper, we suggest to adopt the Land Equivalent Ratio approach to optimise the land use for producing both food and fuels. A similar approach was used for agroforestry systems which combine trees and food crops. Mixing trees and crops was suggested to increase the overall productivity of the land [14]. We intend in this paper to check if such an increase in productivity could also be expected from agrivoltaic systems combining solar PVPs and crops.

2. Designing innovative agrivoltaic systems

When designing agrivoltaic systems, a compromise should be looked for between electricity and crop production, between the solar panel component and the crop component. This compromise could be found by playing upon several characteristics of the solar panel component. Constant tilt arrays intercept less radiation than single-axis trackers, and much less than double-axis trackers [15]. The panel density may also be reduced to allow more irradiation to reach the crop layer. We decided to adopt constant tilt panels in this study.

2.1. The solar panels component

With fixed solar panels of a given size, the optimisation of the system for energy collection results in a sloping angle (that faces South) and a spacing distance between panels (that may be expressed as the percent of ground covered by the vertical projection of the panels) [16]. At our 43.6° latitude North (Montpellier, France), the optimised system has a 33° slope and 63% ground projection, as predicted with the PVsyst software [17]. This can be defined as the reference energy production system. However, in that case, the sun radiation that is available below the panels may not be sufficient to ensure a profitable crop production. To achieve a profitable crop production, a reduced density (or a different sloping angle) of the panels may be required.

The same configuration with one axis trackers, with a twilit angle varying from 10° to 80° southward, would intercept 7% radiation more, resulting in less radiation available for crops (PVsyst software simulation). The only possibility to compromise would be to reduce the density of the trackers.

To allow an easy mechanical cultivation of the crops, solar panels should be lifted to an elevation that is compatible with modern machinery. A 4 m clearance was considered satisfactory. The cost of building a structure that would support either fixed panels or trackers at that height should be carefully evaluated. Supporting pillars must also be well spaced out to allow wide machines (such as harvesters) to pass between.

A yield set can relate the electricity production of the system (expressed in kWh ha^{-1}) and the crop yield (expressed in T ha^{-1}) for varying densities (and/or slopes) of the solar panels. The shape of this function is essential to optimise the systems [18]. An economically based joint production function can also be designed by taking into account the economic value of both productions. Basically, solar panels and crops will compete for radiation, and possibly for others resources such as water, as solar panels may reduce the available water quantity for crops due to increased runoff or shelter effects. However some facilitation processes (positive interactions between solar panels and crops) may also occur, such as the protection of the crops against high temperatures, or an increased water availability for the crops if the rainfall is concentrated and infiltrated on a limited cropped area. The height above ground level of the solar panels has no impact on the total quantity of radiation available at the soil level, but has a very large impact on the heterogeneity of radiation at ground level. The closer to the ground the panels are, the higher the heterogeneity is. Border effects will also be more pronounced if the panels are high above the ground, allowing radiation penetration below the panels from the sides of the arrays, and projecting shadows on the surrounding area.

2.2. The crop component

The main ecophysiological constraint for plant productivity under PV panels results from light reduction. Only scarce information is available on the tolerance to shade of most crop species. In ecology, “shade tolerance” is a plant trait that describes the ability to tolerate low light levels. In agronomy, heavy shade (less than 75% of the natural level of radiation) is usually reducing most plant characteristics. Very few screening studies of the tolerance of crops to shade are available, such as [19] for some specific garden plants of South China or [20] for varieties of *Parthenocissus* lianas. Recently Ref. [21] showed that for maize, plant height, stem diameter, leaf net photosynthetic rate, specific leaf weight, above ground dry matter accumulation, and the number of kernels per row were all significantly reduced under 50% shade, and that the varieties may be classified as shade-tolerant or shade-intolerant. Common beans are reputed to tolerate shade well, but Ref. [22] showed that shade also reduced significantly bean yield in a rubber agroforestry system. Similar results were also published on perennial crops such as alfalfa [23], but most commercials crops were never studied under shade. It is therefore extremely difficult to recommend some species for their adaptation to shade tolerance.

Moreover, interactions between radiation stress and other limiting factors for plant production may happen. Thermal stresses or photoinhibition processes sometimes limit plant productivity, and may increase in the future as a result of climate change. Ref. [24] showed that banana optimises light use at a significantly high shade level. The optimum shade level for photosynthetic productivity would be one at which the level of photosynthetic photon flux density is high enough to saturate CO_2 assimilation but low enough to induce shade acclimation and reduce photoinhibition. For banana, this saturation level was around 1000 $\mu\text{mol m}^{-2}\text{ s}^{-1}$, a low light level typical of the tree-based intercropping systems in