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Reducing Earth's Greenhouse CO_2 Through Shifting Staples Production To Woody Plants

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Abstract

Two systems of intensive food and fiber co-production using woody plants are proposed. Potential effects on atmospheric CO_2 are discussed, and could be highly significant if such systems were widely implemented. A maximum carbon fixation rate of 1.82 X 10^{13} g/ 10^6 hectares/ year is calculated, more than triple the average for maize. If all United States croplands planted to maize or soybeans in 1986 (55.5 million hectares) were planted to such woody crops, at least 1.01 X 10^{15} g carbon/year would be fixed, a large fraction of which could be sequestered for long periods of time or substituted for fossil fuels.

This paper considers a possibility which has so far been discussed little or not at all. Yet it is an option which might do much to ameliorate the increase of CO_2 in our atmosphere. It deserves careful examination.

I propose that we consider gradually shifting our agricultural system away from its current reliance on annual plants, and instead increasingly rely for foodstuff staples production on woody perennial plants. It may actually be possible to replace maize, rice and wheat with nuts and other kinds of fruits grown on woody plants. What I am suggesting is something substantially different from the commonly discussed "tree crops" concept of J. Russell Smith, which is concerned with basically traditional gathering of tree fruits; different from horticulture, which deals mostly with "luxury" crops; and different from "agroforestry" which calls for growing trees and crops together. The concept proposed here I call "woody agriculture": the intensive production of protein, carbohydrates and oils from highly domesticated woody perennial plants. Please note that I do not say "trees"— while one of the systems discussed here would use trees, others do not.

Why bother to contemplate such a sweeping change? Because a look at the distribution of solar energy available for photosynthesis each year clearly shows that annual crops <u>cannot</u> capture even 50% of it, whereas woody plants develop leaves very early, and are capable of capturing light and CO_2 throughout the growing season, even in cool weather (see figures).

Our current dependence on annual plants was inherited from our remote ancestors. There were excellent reasons why primitive peoples first beginning to rely on agriculture should utilize annual crops, (e.g.. the ability to harvest a crop one year after a migration to a new home site) but I contend those reasons have become obsolete. It may in fact be greatly to our benefit to begin a shift away from annuals and look to woody plants for the bulk of world food production. Currently, the only woody plants seriously contributing to international staples production are the palms, responsible for a substantial portion of world edible oils. Palms, however, grow in the tropics, where light and temperature are nearly stable. This paper is limited to discussion of temperate latitudes, where the culture of annual crops often requires long periods of time when fields are devoid of any photosynthetic potential, and because the potential for increased carbon fixation by the vast temperate land areas devoted for generations to annual crop production has been largely ignored in discussions of the global carbon budget *(14,15)*.

This paper seeks to convince the reader of the following points: that the benefits of woody agriculture could be immense; that woody agriculture could make a substantial contribution to control of atmospheric CO_2; and that all of the systems components for a woody agriculture either exist today or could be developed with current technology. Specific examples of woody crop systems that might be rapidly developed as staples are described below.

The quantitative estimates of the impact of extensive woody agriculture on atmospheric CO_2 offered here are simplistic, and can serve only to indicate the general magnitude of the effects. There are so many different factors interacting that complete estimates will require the attention of a specialist in mathematical models, which I am not. Several important beneficial effects are not estimated here.

Benefits Of Woody Agriculture

The benefits of using woody plants for agricultural purposes are many, and the reasons for shifting from annuals are compelling.

• Woody plants are capable of photosynthesis over a much longer portion of the temperate growing season (see figures). They do not, in general, photosynthesize over that entire time as efficiently as some crop plants can during the peak growing season, but the capability for photosynthesis over so much more of the growing season is very significant.

In addition to the phenomena described in the figures, even when deciduous trees have dropped their leaves the green twigs conduct photosynthesis whenever temperatures permit; contributing significant amounts of carbon fixation. As a measure of the potential photosynthesis: in April, when maize fields are bare, a wild oak forest in Minnesota had 10,300 grams/hectare of chlorophyll, in the oak twigs. By comparison, at its maximum in August, a field of maize contained only 13,000 g/ha, while the oak twigs and leaves then held 24,000 g/ha. In November, with the maize at 0 again, the oak twigs contained 7,000 g/ha *(3)*. Double-crop systems for annuals, such as the southern "corn belt" practice of winter wheat-soybeans, will do better than single-crop maize, but will still entail critical months where the photosynthetic potential of the field is very small.

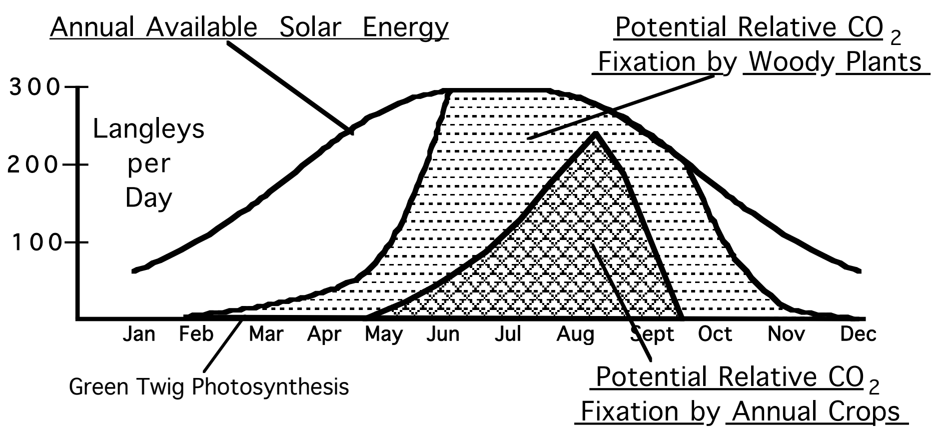
• Woody plants are by their nature more effective traps for light energy. Their more extensive and complex canopy structure, the early leafing, all lead to more thorough capture of available light. In a healthy forest, very little light penetrates to the ground; in a maize field, there are large amounts of unutilized light hitting the ground for most of the growing season.

• Deep rooted woody plants are able to sustain photosynthesis through moderate dry spells in ways that the initially shallow rooted annuals are unable to— when a young annual has to suspend photosynthesis because of a lack of water, established woody perennials will tap deeper water supplies and continue to fix CO_2 .

As a result of the above three factors, temperate woody plants do lock much more carbon into biomass each year than temperate annuals. Illustrating the potential of woody plants, experimental stands of hybrid poplars bred for harvestable biomass have produced as much as 27.8 Mg($=10^6$g)/hectare/year of dry, above-ground biomass *(9)* ; whereas the comparable figures for maize, including seed, average only 10-11 Mg/ha/year *(10)*. I believe it is justifiable to use a maximum attained figure for temperate woody biomass, which depended on optimized growing conditions, as the technology and genetics of such systems are relatively young, and are still improving.

Converted to carbon {0.5 X woody plant biomass, 0.43 X maize *(15)*}, this would be approximately 1.4 Mg carbon/ha/year for woody plants, and 4.5 Mg for maize; counting above-ground material only.

Most of the carbon fixed by annual crops is cycled back to the atmosphere as CO_2 or methane within a year. Much (perhaps half) of the carbon fixed by woody plants, however, would be removed from the global carbon budget for a variable but relatively long time; decades or sometimes hundreds of years.



Woody plants, with their rapid early leaf deployment, multiple leaf layers, and longer growing season, capture significantly more solar energy than traditional annual crops. This means more, potentially much more, CO_2 fixed.

• Much of the below-ground biomass generated by deep rooted woody plants would be carbon removed from the yearly global carbon cycle for a very long time span. Unlike annuals, where most of the root mass is in the top layer of soil, tilled after the growing season, and rapidly converted to methane or CO_2, woody roots penetrate much deeper; 5 to 15 meters being common. Carbon used for constructing woody root systems would be locked out of the atmosphere as long as the plant remained alive, and after death of the plant, decaying root systems 5 meters deep would return very little carbon to the surface. Woody plant root systems vary greatly, but never contain less than 20% of the dry weight of the above-ground system, including leaves (10). 30%, when fine rootlets are included, may be a conservative average. This would mean an additional 4.2 Mg/ha/year of carbon fixed.

Speculatively, it seems likely that some of the carbon used to form deep roots will ultimately be entirely removed from the biological carbon cycle. When deep roots die, their decomposition may result in the formation of carbonate ions, which would then readily migrate in groundwater. This carbon would then become part of the geological carbon cycle, perhaps to be deposited far from the original tree as calcite crystals, and locking the carbon out of the atmosphere on a geologic time scale.

• Some of the above-ground harvestable wood biomass produced as a by-product of staple food production would be used for energy generation to partially replace fossil fuels. In this way we would be recycling atmospheric CO_2 instead of constantly adding fossil carbon, slowing the build-up of greenhouse CO_2.

• Fossil fuels currently used in agriculture for yearly seed bed preparation and cultivation would be greatly reduced. With woody plants, it is probable that fields would need to be replanted only every 5-15 years, or even in some cases once in 100 years. It is possible fossil fuel use for maintaining woody agriculture plantings could be reduced by as much as one half from present requirements.

• The benefits of trees as carbon sinks are widely recognized, but at present trees are usually only considered for planting on marginal, i.e.. less productive, lands *(2)*. The ability to produce staple crops from woody perennials would enable us to put photosynthetic cover on our most productive and fertile lands; lands that are currently mere naked soil for much of the growing season. The amount of land benefiting from perennial cover could be greatly extended, and carbon capture very greatly increased.

In 1986 in the United States, the top ten maize producing states planted 23,836,000 hectares of maize; the top ten soybean producing states planted 19,862,000 hectares of soybeans; for a total of 43.7 million clean-cultivated hectares for just those two crops (fewer hectares were planted in 1987 and 1988, in an effort to reduce crop surpluses)*(8)*. At a rate based on the above calculations of theoretical potential, intensively cultivated woody plants would fix 1.4×10^{13} g carbon/10^6 ha/year above-ground and 0.42×10^{13} g carbon/10^6 ha/year in roots, or, for those 43.7 million hectares, 0.795×10^{15} g carbon/year. If all United States croplands planted to maize or soybeans in 1986 (55.5 million hectares) were planted to such woody crops, they would fix 1.01×10^{15} g carbon/year.

• Woody plants can produce far more leaf litter than annuals, and decreased tillage would mean less rapid oxidation in the upper soil layer: there is room to store substantial amounts of carbon in the soil as increased organic matter. Current cropping and tillage practices often deplete the organic content of soils. In woody agriculture, much of the abundant leaves, litter, and any woody material not harvested for fiber would eventually be incorporated in the soil, resulting in enriched, more water retentive, and more productive soils; and CO_2 removed from the atmosphere. (Some undisturbed forest soils typically have low organic contents, but woody agriculture soils would be under a completely different development regime, and might be more comparable to the highly organic prairie soils.)

How much carbon would it take to raise the organic content of the top 15 cm of the US cornbelt by 1%? The US Soil and Conservation Service estimates the weight of 15 cm of soil, at a bulk density of 1.3 (a reasonable average), to be approximately 2.24×10^9 grams/hectare. For the same ten maize and soybean producing states mentioned above, a 1% increase in soil organic matter for the top 15 cm of the 43.7 million hectares planted to those crops would require 98×10^{15} g of organic material. Using a conversion factor of 1.7 g of "organic matter" to 1 g of carbon, this is 57.6 X 10^{15} g carbon (1.3 X 10^{15} g carbon/ 10^{6} hectare).

Increasing soil organic matter is a slow process, but considering the possibilities of adding more than just 1% organic matter to some soils, in woody agriculture fields around the world and in many climates, it is clear that this is a non-trivial storage potential. Carbon in organic material of temperate forest soils can have a "residency" of more than 100 years *(15)*. The soil could be a significant and highly desirable sink for some of the present atmospheric carbon surplus, providing systematic ways can be found to get the carbon into it. Policies encouraging woody agriculture would be one way.

Other Benefits

Besides improving the greenhouse CO_2 balance, there are other environmental benefits that would accompany the use of woody plants. The fact that the soil is not tilled on an annual basis would of course lead to greatly decreased soil erosion, both by rain splash and wind. Perennial cover holds water far better than annual systems by trapping moisture in the form of snow and fog, holding rainfall better, and allowing better penetration into the soil.

Woody agriculture would be far more sustainable than systems using annuals. Besides the above benefits to soil and water, the deep roots bring otherwise unavailable minerals to the surface for the enhanced nutrition of later generations- the leaf litter enriches and renews the soil in ways annuals do not.

Standard objections

Woody plants are seldom considered as having any serious potential for intensive agriculture because there are a series of unstated or unexamined assumptions about them which may in fact not be valid.

It is assumed that because woody plants put so much energy into wood, they cannot be as productive of seed as annuals. The comparisons made between crop and tree fruit yields are often inappropriate, however, as they are drawn between annuals domesticated for millennia and nearly "wild type" woody plants which have been selected for fruit or seed production for only one or two generations. In addition, it is clear that woody plants can produce much more photosynthate in a year per unit of land than annuals (above), and thus should be able to make both wood and seed. {Similar assumptions have been made in the past about the productive capabilities of herbaceous perennials, but measured yields belie the assumptions *(12)*.} There are records of many woody plants producing phenomenal crops *(4, 5)*. In the case of wild chestnut, crop production takes place annually and is accompanied by faster wood production than other tree species in the same forest *(6)*.

It is assumed that woody plants cannot be bred fast enough for staple crop needs because wild type woody plants usually require several years for each generation, sometimes up to 20 years. Precocity in woody plants, however, is not difficult to find. I have personally bred chestnut hybrids that have flowered 2-3 months after germination of the seed, producing useful amounts of pollen *(7)*. With an intensive effort similar to that now made for annuals, woody plants could certainly be bred fast enough to respond to disease challenges.

It is assumed that the usually high cost of clonal woody plantings could not be justified by the rather low prices received for staples. But the advent of plants from tissue culture, and the increasing potential for "artificial seeds" makes it likely that with economies of scale planting stock for woody agriculture could be very reasonably priced. Tissue culture also makes it possible to increase desirable genotypes fast enough for large scale needs. Hybrid poplar stands are currently established using unrooted cuttings *(9)*.

Requirements

For any suggested alternative form of agriculture to be worth considering, it must meet several specific requirements.

•It must be sufficiently recognizable to current farmers so that they can adopt it.

•It must be mechanizable. There is not enough hand labor in the entire world to pick the US maize crop. There must be ways to mechanize planting, care, and harvest.

•The mechanization requirement means that the crops themselves must be standardized— they must grow and ripen uniformly. For woody plants, this means there must be a way to produce and plant huge quantities of clonally propagated plantlets.

•There must be enough genetic malleability to the species being domesticated so that useful varieties can be identified and improved.

•There must be ways to very rapidly breed or otherwise produce new varieties resistant to newly evolved diseases.

•Production of a salable crop must occur within a very few years of planting, at most 3.

•The crop or its products must be stable in storage.

•The productivity, quality, and versatility of the new crops must equal existing crops.

Woody plants can almost certainly meet each of these requirements.

Specific examples

The paragraphs below show how, using the specific examples of chestnuts and hazelnuts, these requirements can be met, and why the usual objections may not apply to systems that are nearly available to us today.

I want to emphasize that though chestnuts and hazelnuts are discussed here, the kinds of agricultural systems being proposed are by no means limited to those two species: I use them for examples because I work with them, and because they may be close to actual utility. There are many other woody species which could with extensive but straightforward breeding be domesticated to the point where they would be suited for woody agriculture, in many latitudes, for many purposes *(4, 5, 6*).

Could chestnuts and hazelnuts fit into current needs and markets? Yes. Chestnuts are comparable to maize for protein and feed value, being lower in oil but with higher quality protein— the limiting amino acid is isoleucine. When dried like maize, the nutritional value is stable. They are excellent animal feed and there are numerous traditional human culinary uses, ranging from soup to bread. Hazelnuts have good protein also, but have an oil content high enough to make them subject to rancidity in long term storage. Processing might involve pressing out the edible oil, and marketing the stabilized dried cake for both human and animal use. Both chestnuts and hazels also have considerable, though largely uninvestigated, potential as industrial feedstocks for products ranging from ethanol to plastics.

• The first specific proposed crop system involves harvesting chestnuts or hazelnuts on an alternate year basis, taking both nuts and a wood "biomass" crop every other year from established root systems. Envision a field, previously planted to maize, now planted solidly to a highly productive chestnut cultivar, plants being spaced about 1 m X 1 m. After a mechanized planting, the plants should take no more than 3 years to bear their first crop. At that time, they would be between 1.5 m and 2 m tall. In October, when the nuts are ripe but before they drop, such a field could be mechanically harvested with a combine, very much in the fashion of maize. A combine would strip nuts, husks, and some leaves from the branches, thresh out the nuts and blow the shattered husks back on the field.

A month later, after the woody stems and branches have gone completely dormant, the same field is harvested again; this time with a machine that cuts all the woody stems right down to the ground. This wood is chipped by the harvester, and sold as a biomass or fiber crop. The main stems of such plants are likely to be 3 to 6 cm in diameter, yielding chips large enough for chipboard production. The wood might also be extracted for salable chemical compounds (tannic acid is a distinct possibility) and ultimately put to use as fuel or pulp.

The year after harvest, the plants re-sprout from the established root system, growing 1 to 2 m high. Both chestnut and hazel seem to have the ability to re-sprout in this fashion for many years. The second year after being cut to the ground, they bear nuts once more, and are harvested again.

The field could be laid out in alternate strips, so that adjacent rows are in successive years of the rotation. This would increase protection for the soil and maximize edge effects for the bearing strips.

Benefits of cutting the wood to the ground every other year include:

Less concern about damage done to the wood by the nut harvesting machines, since the wood will shortly be harvested also.

Plants being harvested will always be the same size, simplifying machine handling.

Removal of old wood should reduce the need to control some diseases.

All pruning is eliminated.

A second salable crop is generated.
Marketing options are increased for the grower.

Could plants capable of such performance be found, or created? To a very limited extent, I have already grown a few multiple-species chestnut hybrids on my farm in Minnesota which have performed in just this way, bearing almost a kilogram of fresh nuts per root system *(7)*. Hybrid hazelnuts appear close to the same potential. It even seems possible that cultivars might be developed that would bear nuts each year, on new sprouts; this has already been accomplished with raspberries.

- A second type of crop system would use more conventional orchard technology, except that breeding would take the place of labor intensive pruning practices. Trees would be bred to take the approximate form of Lombardy poplars. Denser planting in early years would give way to wider spacing as the trees gained height, with an accompanying harvest of wood. With proper spacing to allow light penetration, such plantings would be very efficient collectors of solar energy, and even trees growing to heights of 50-60 feet would be able to fruit over their entire surface. The soil surface between trees might be planted to a tailored, shallow rooted perennial legume, which besides stabilizing the soil would fix some nitrogen for the crop system and also fix carbon when sufficient sunlight penetrates the overstory. Harvest would be by sweeping up fallen nuts or shaking them out of the trees; machines for both those tasks already exist. Large wild chestnut trees have already demonstrated the ability to bear heavily over the entire crown, year after year, so long as they receive full sun.

Advantages of this system are that:
Replanting might need to be done only once in 50-100 years.
If the system were used widely, it would allow very large amounts of carbon to be tied up for long periods of time.
The large stems of such trees would have multiple marketing possibilities, giving the farmer increased flexibility with his crop.
Pruning is genetically eliminated.
It is very similar to current orchard systems, making it more readily adopted.

Conclusions

Many other woody agriculture methods can be proposed. While the future of any such system is speculative, the potential ability of woody agriculture to remove CO_2 could be very great, and could constitute a major contribution to the eventual control of greenhouse gases. Not only is the present maximum carbon fixation rate of woody plants more than triple that of maize {1.82×10^{13} g carbon/10^6 ha/year above and below ground for woody plants *(9)*, vs. 4.8×10^{12} g carbon/ 10^6 ha/year for total maize field, including weeds*(10)* } but a large fraction of the carbon fixed in woody agriculture would not be immediately returned to the atmosphere, whereas most carbon fixed in annual agriculture is returned as CO_2 or methane within a year of fixation *(15)*. With some 1,500 X 10^6 ha under cultivation world wide *(15)* it is easy to see the potential impacts of woody agriculture could be tremendous.
How much carbon could the topsoil of temperate regions hold as organic matter from increased leaf litter? Soil will absorb 1.3×10^{15} g carbon/ 10^6 hectare for a 1% increase in organic content of a 15 cm soil layer.
These are simplistic initial estimates. For several important effects I have not yet prepared numerical estimates; the attention of a mathematical models specialist is needed. How much less fossil fuel would it take to grow crops that only had to be planted once every 5-10-100 years, instead of every year, or twice a year? How much fossil fuel could the woody biomass byproducts replace? How many forests could be left standing because fiber was being supplied by agriculture?

It should not be necessary to give up high crop productivity to achieve the desirable effects on atmospheric CO_2. The demonstrated ability of temperate woody plants to fix more than triple the carbon per year that maize can is an excellent indication that woody plants can be developed which would allocate a portion of that photosynthate to human-utilizable seed, in quantities at least equal to the present production of annual plants. Measured yields of woody plant fruit and seed, from systems and trees which in my opinion are primitive compared to the visible potential, already approach yields attained by annual crops *(4, 5, 6)*. It is entirely reasonable to believe that well developed woody agriculture systems would not be less productive than traditional agriculture, and an optimist might find reason to believe woody agriculture could actually be more productive than current practices.

Although this paper has been limited to considering temperate applications of woody agriculture, similar systems could certainly be developed for the tropics as well, and might be expected to utilize the extra heat and solar energy very efficiently. A well tailored tropical woody agriculture system might go a long way towards stabilizing the environment in those areas, once rain forest, now being so rapidly degraded by the need for constant tillage. Perhaps such systems could make more realistic the hope for "sustainable development".

No large woody agriculture system is going to appear soon; none will appear at all without increased appreciation of the benefits and a greatly enlarged research effort. Replacement of any substantial portion of annual crops could only be a gradual development; but the potential benefits are immense.

Woody agriculture is tenable today. The system component requiring the most development is the plants themselves, but there is no reason why suitable varieties cannot be bred. The Native Americans gave us the most compelling example of what transformations are possible through domestication. Starting with the wild grass teosinte, they created maize, an accomplishment modern workers have not equalled. Nothing similar has ever yet been attempted with woody plants, but the prospects are excellent. Woody plants are genetically rich, consistently containing much more variation than annual plants *(11)*.

Perhaps most importantly, woody agriculture represents a new option. And we are facing a future where Homo sapiens will assuredly need options.

After-word and Acknowledgments: There are many considerations involved in the theory, rationale, and implementation of woody agriculture which cannot be discussed here because of space limitations. Those interested are encouraged to contact the author. I wish to express my deep gratitude to the following persons for their comments and suggestions for this paper: K. Davies, D. Egloff, R. Jaynes, R. Knutson, D. Lawrence, G. Miller, M. Widrlechner.

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