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VETIVER SYSTEM: REVERSING DEGRADATION ON- AND OFF FARM, TO KEEP SOIL CARBON IN PLACE, BUILD UP ROOT BIOMASS, AND TURN DEGRADED AREAS IN BIOFUEL SOURCES

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[1] https://books.google.co.ke/books?id=eprNBQAAQBAJ&pg=PA323&lpg=PA323&dq=vetiver+carbon+pinners&source=bl&ots=yGcn9JBcZd&sig=TqcS7Qd_ETx3mMFNz-OVGAWHSog&hl=en&sa=X&ei=KFauVI2CMoH9UMiSg9gC&redir_esc=y#v=onepage&q=vetiver%20carbon%20pinners&f=false

Introduction

This paper focuses on the remarkable capacity of Vetiver grass (Chrysopogon zizanoides) for atmospheric carbon sequestration and soil carbon capture and storage.

Vetiver System (VS) semipermeable hedges reduce loss of soil, moisture, and fertility and are directly important for farmers and food production (Truong et al., 2008).

Vetiver, due to high biomass production, is great for production of biofuel (dried grass bunches, or pellets for home cooking, feed for ethanol plants and gasifier installations feeding the grid and for residual biomass from essential oil plantations for furnaces).

Vetiver's promise of soil carbon capture carbon sequestration is immense, given Vetiver's enormous capacity to produce biomass, and its impressive deep root system that can possibly capture more carbon than any other grass. Most plant carbon biomass research focuses on grassland grasses or trees, but vetiver is not that kind of grass nor a tree. Yet it has to fit into databases on carbon sequestration and storage that are currently developed.

Technologies, methodologies, and algorithms need to be improved to allow measurement of vetiver carbon sequestration, capture, and storage. This requires observations under different climate and soil conditions, as well as different applications of the VS. India and China, having good research institutions and a wide range of growing conditions, are well placed for this (Pinners, 2011).

Biofuel from Degraded Areas

Biofuel from Vetiver grown as a field crop

In nearly all applications of vetiver, as VS, the grass is planted as a dense hedge, typically placed along contour lines or (when farms are small) on boundaries of fields, embankments, or edges of water courses (Truong et al., 2008). This applies for on-farm applications, bioengineering for protection of slopes (infrastructure), and artificial wetlands. Perhaps the odd exceptions are just two: floating vetiver for treatment of wastewater in ponds (photo), and the planting of vetiver as a field crop, for biofuel.

As a field crop, producing about 100,000 plants/ha (0.3 x 0.3m spacing), it provides up to 120 t of dry biomass per year per hectare on soils of reasonable depth and fertility. On saline soils in the Dominican Republic, dry Vetiver biomass production is reported at 70 t/ha. For modelling it is fair to use the 100 t/ha when we have deep and good soils, and 80 t/ha for poorer conditions. (From Truong, P. Personal Communication, 2013)

Not displacing food crops for fuel production

Vetiver thrives in places, and support revegetation under difficult conditions where nothing else will grow or replace conventional nonvegetative engineering. For smaller scale use, it could be obtained from road cut-and-fill batter and drains (photo 1-3), landslides, gully rehabilitation work and decommissioned waste dumps where toxic leachate is recycled back on the dump (photo 4-6), on highly erodible canal banks made of coastal acid sulphate soils, shifting dune sand and degraded laterite soils (photos 7-9).

Vetiver is well placed as a potential furnace feedstock, and has the added advantage in that it could be grown on marginal lands. Vetiver could be grown on a large scale, producing high yields with very little supplementary irrigation to be used for biofuel in ethanol plants, in conventional coal-fired furnaces (as in the Dominican Republic example), or in the latest state-of-the art gasification installations that have recently been developed for woodchips.

In the following example, from the Dominican Republic, vetiver is grown on saline soils. In northern and northwest India and Pakistan, there are huge areas of saline irrigated land with high water tables (marginal to agriculture because of poor drainage that has led to saline soils and saline ground water). Additionally, vetiver would help rehabilitate saline land so that it might again be used for profitable purposes. This was done in the 1950s on

Ussar lands in Uttar Pradesh where vetiver was used to rehabilitate saline land where little else grew (The National Research Council, 1993).

In some parts of India, it is traditional to move hand-cut sugar cane and grass to nearby cane and paper processing plants. There would be little difference in doing the same for vetiver.

Cellulosic Ethanol

In the United States, research is being carried out on plants such as *Miscanthus*, switchgrass, and corn as potential feedstock for cellulosic ethanol plants. The table below shows the characteristics for an ideal biomass fuel.

TABLE I

Characteristics of an ideal biomass energy crop present (+) in corn, short rotation coppice and *Miscanthus*, developed in part from Long (1994). and Khosla (2006).

Crop characteristic	Corn	Short-rotation coppice	*Miscanthus*
C_4 photosynthesis	+		+
Long canopy duration		+	+
Perennial (no need for annual tillage or planting)		+	+
No known pests or diseases			+
Rapid growth in spring to out compete weeds		+	+
Sterile; prevent 'escape'			+
Stores carbon in soil (soil restoration and carbon sequestration tool)		+	+
Partitions nutrients back to roots in fall (low fertilizer requirement).			+
Low nutrient content i.e. < 200 mg MJ^{-1} nitrogen and sulphur (clean burning)		+	+
High water use efficiency	+		+
Dry down in field (zero drying costs)			+
Good winter standing (harvest when needed; zero storage costs)		+	+
Utilizes existing farm equipment	+		+
Alternative markets (high quality paper, building materials and fermentation)	+	+	+

Source: http://www.aces.uiuc.edu/DSI/MASGC.pdf

Vetiver grass meets all the characteristics of *Miscanthus sp.* and more. Most importantly, it is a drought tolerant, long-term perennial crop that needs only moderate inputs to be productive (Grimshaw R. , The Vetiver Network International, 2008)

The dry matter yield of *Miscanthus* is, after two years of stand development, about 25 t/ha (University of Florida, 2012) whereas that of vetiver, if planted as a crop, is estimated at about 100 t/ha (Pinners, 2011). Vetiver productivity, in particular below ground, is superior to *Miscanthus* (in photos: 1. *C. zizanioides*, or Vetiver as we refer to here, in the background, compared to *C. nemoralis* in front; 2. vetiver, 6 months old; 3. vetiver plant on the right, 9 months old; 4. in China, an effort to uproot a plant).

Coal-fired furnaces for electricity

When a medium-sized power plant adds biomass to its mix, its global warming emission reductions are equivalent to taking 17,000 cars off the road (ALSTOM, 2011).

Vetiver has an energy value of 16.3 GJ t^{-1} compared to petroleum 41.9 GJ/t, coal 12-30.3 GJ/t, dry wood 19.8 GJ/t, and sugar cane bagasse 9.3 GJ/t. These nonvetiver biomass sources are used as feedstock to generate electricity.

The advantages of vetiver feedstock over other fuels are:

1. As it is entirely renewable and in the burning process does not add net carbon amounts to the atmosphere.
2. CO_2 reduction from coal power plants can be expensive ($100-$200/t for some methods), but co-firing biomass with coal (coal in quantities as small as 15% of the biomass) gives 95% cost reduction compared to using coal only;
3. Biomass has much lower sulphur content than even low-sulphur coal (which is costlier than regular coal), so there will be less SO_2 release into atmosphere;
4. Nitrous oxide emissions from biomass combustion are also expected to be less than from coal firing processes;
5. Coal mines release gases for a long period; for a vetiver farm this is only temporary, when the field is established (the crop remains permanently, so no annual ploughing is required).

Boucard's biofuel case (a 50 Mw power plant in Barahona, Dominican Republic)

- Under tropical conditions, under irrigation or good annual rainfall, dry vetiver leaf production of 70 up to 80 t/ha.yr;
- As it is never a good idea to burn wet fuel (energy is used to evaporate the water, and steam reduces furnace temperature), Vetiver is dried prior to burning, to reach a moisture content of about 10%, which takes 3-4 days sun drying;
- Planting Vetiver for fuel is one of the easiest and safest farming operations: unlike sugarcane, Vetiver plantations needs no re-planting, it can be harvested annually at any time of the year, has no diseases or weather damage, and production can go on for more than 20 years, by just adding fertilizer;

- Owning land and farming operation, once the plantation is established, Boucard estimates production of Vetiver biomass costs to be below US$16.5/t;
- Baling is done with a standard hay baler; after 3-4 days sun drying moisture is 10%;
- Dry grass calorific value: 16.3 GJ/t (about half of that of coal)
- Modern thermal power plants needs about 900 t/day of vetiver bales to produce 50 Megawatts (or 450 t/day coal import from Colombia, providing 30.3 GJ/t)
- 900 t of vetiver bales more than equal 450 t coal, to be harvested from 12.5 ha in one day; so, *to run a 50 Mw plant 365 days year^{-1} requires 4,563 ha, surrounding the plant***;** unlike sugarcane, vetiver does not need re-planting as it simply grows back, with natural rainfall, and can be harvested any time of the year for 20 years or more (just add some fertilizer). The raw cost of producing vetiver biomass fuel is no more than US$ 16.5/t, once the plantation is established.

Cost of producing 1 GJ (in 2009):

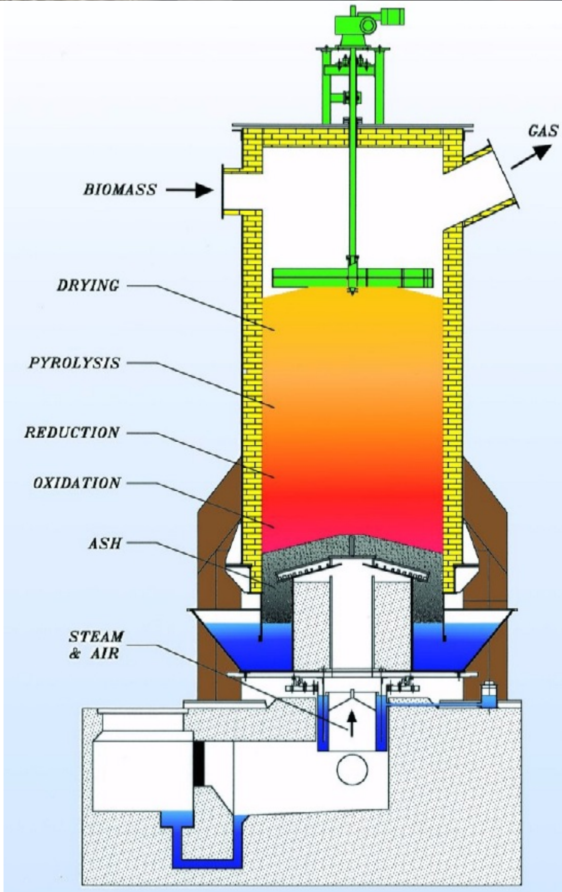
- Vetiver gives 16.3 GJ/t dry leaf, so we need 64.4 kg, it costs US$ 1.06
- Cost if coal: 32.6 GJ/t as cheapest fuel costs US$ 40/t → US$ 1.60
- Cost if crude petroleum: US$ 655/t crude petroleum, which has 42 GJ/t → US$ 16.

Vetiver is the most lucrative use for tropical farmland (Boucard, 2009)**.** If third world countries realize this, one of the biggest problems will be to ensure that food crops are not displaced for fuel production!

New technology gasification for electricity

In Kenya an initiative is in preparation to use vetiver (grass bales) as an alternative biofuel in a wood chip to electricity plant (BTE: biomass-to-electricity). The initiative is from The African American Environmentalist Association (AAEA), in cooperation with National Clean Fuels (NACF), and Dyson Engineering and Technical Services (DET Services). Vetiver grass would be gasified with the methane burned in a turbine engine to produce electricity. Comparing heat content:

- Petroleum has on the average 42 GJ/t
- Coal has 28 GJ/t
- Dry wood has 20 GJ/t
- Sugar cane bagasse has 9.3 GJ/t
- Dry vetiver Grass has 16.3 GJ/t.



Sketch of updraft gasifier (source: **Volund Systems**, Waste and Energy Technologies)

The source of vetiver grass bales is to be a combination of nearby farming of vetiver and delivery from other farms; a combination with sugarcane bagasse may also be tried. The idea is still in a very early stage and a feasibility study is being prepared.

Gasifiers generally run on a portion of the supplied feedstock as well as converting the balance of it to a fuel for other applications. Biofuel-generated gas is a syngas that is produced by thermal gasification of biomass. It is the result of two high-temperature reactions (1292 °F): an exothermic reaction where carbon burns to CO_2 but is then reduced partially back to CO where carbon reacts with steam, producing carbon monoxide (CO), molecular hydrogen (H_2), and carbon dioxide (CO_2). In several gasifiers, the actual gasification process is preceded by pyrolysis ('a thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen. Pyrolysis typically occurs under pressure and at operating temperatures above 800 °F'), where the biomass or coal turns into char, releasing methane (CH_4) and tar rich in polycyclic aromatic hydrocarbons (PAHs). Other gasifiers are fed with previously pyrolysed char. Biofuel-generated gas is flammable because of the carbon monoxide, hydrogen, and methane content. A gasifier takes biomass as fuel and is burned incompletely in a firebox, producing solid ashes and soot (which have to be removed periodically from the gasifier). The gas can then be filtered for tars and soot/ash particles, cooled and directed to an engine. Most of these engines have severe purity requirements of the gas, so the gas often has to pass through extensive gas cleaning in order to remove or convert (i.e. to "crack") tars and particles. The removal of tar is often accomplished by using a water scrubber. Exhaust gas emission levels from an internal combustion engine is significantly lower on biofuel gas than on petrol. Especially low are HC emissions. A normal catalytic converter works well with biofuel gas, but even without it, emission levels less than 20 ppm HC and 0.2% CO can be easily achieved by most automobile engines (Wikipedia) and see Technology brief (Lunds_University, 2003).

Other fuel ideas are discussed in 'flash pyrolysis' (Forti, 2013) (in Italian).

R&D on combustion

More research on perspectives and constraints is required. Some estimates indicate that if income from biomass for fuel is combined with credits for carbon offsetting, economic rates of return would be in the order of 15%. These estimates are made a few years ago when oil prices were lower, so the return rate would be even higher today.

There are two challenges that need further research:

1. Vetiver's high nitrate absorption does not all go into the air in negative way, if primary N combustion product is elemental nitrogen (N_2, which is the bulk of the atmosphere). But: poor combustion can lead to all sorts of noxious compounds. Much of knowledge about combustion is directly applicable to vetiver, but some practical research may be needed to check noxious compounds emission. The factors that affect results of combustion are:
   - N content of foliage: in vetiver this is not particularly high;
   - How the grass is "cured", and how it is burned in coal-fired units
   - Impact of silica on furnaces.
   - Silica in foliage: Vetiver has higher silica levels are higher than in many other grasses, increasing with age, and variable per genotype; it is consolidated in leaf as mineralized "phytoliths" (whose shape is unique to each species). Silica (and other minerals) can create ash disposal burden in combustion as well as aerial fly ash deposition, plus silica itself can serve as a flux in combination with other

elements than can wreak havoc in furnaces. So silica is a downside to burning vetiver (compared to *Miscanthus*), but how serious is that?

And possibly complex silicate salts capture and precipitate some of heavy metals, sulphur compound, nitrous oxides in mixed combustion reaction, preventing them from escaping through the stack. This is relevant for large furnaces and combustion systems, where there is great concern for emissions. Another plus for Vetiver?

2. Silica affecting the furnace: Vetiver forms a glassy type of "klinker" which stays in furnace with ash (complex oxides & salts). Vetiver contains so much silicates (more than in Miscanthus), it tends to flux firebrick by lowering the melting point of brick. This is why furnaces in Texas (where spent wood from extraction process was burnt at very high temperatures >2000^{o}F), had to go to a brick with 70% alumina content, to prevent *fluxing*. Cheap bricks with only 50% alumina melt like butter. High alumina bricks are costly and there are thousands of bricks in a large furnace.

Carbon Sequestration, Capture, and Storage

There are two areas describing carbon sequestration:

1. *Sequestration of carbon* (from the air) which is - simply put - a way to offset carbon emission elsewhere. Natural vegetation when in a balanced, normal life cycle does sequester carbon as well as emit carbon, so that would be neutral. But vetiver System has the ability to reverse degradation, to transform a biomass-poor situation (degraded land, gullies, roadsides) into something with much more biomass.
2. *Carbon capture and storage* (from atmosphere via the vegetation into the soil).

Carbon sequestration

Vetiver is one of the world's most unique plants in its range of applications, and also has to be one of the world's best carbon-sequestering plants. Vetiver's advantage over other candidates is best summarised when referring to its high potential for biomass production in combination with its other characteristics that support a wide range of applications.

From a spatial perspective the carbon sequestration can be classified as:

1. *Increasing biomass in-situ* (3-9 kg/metre depending on soil and rainfall) where vetiver is planted it increases biomass on mostly barren land and water surface e.g.:
    a. planted on degraded lands;
    b. vegetating mining sites;
    c. decontamination of water in artificial wetlands or hydroponic (in wetlands vetiver doubles Kikuyu grass effectiveness in biomass production and N uptake (Vieritz, Truong, Gardner, & Smeal));
    d. planted on infrastructure slopes, for example, road- and railway embankments and gullies that would otherwise be poorly vegetated or paved with any combination of stones and concrete (sand, cement steel), or around houses, on compounds (around L. Victoria compounds, landing sites, footpaths and unpaved roads are 2.2% of the study area but contribute 85% to soil loss (De Meyer & Jean Poesen, 2011). *Photos: Machakos March 2013 and Nyanza 2011 (Biogardening Innovations).*

e. replacing the inadequate (out-dated) engineering structures for soil conservation (e.g. the constructed contours that typically are not so well vegetated). In Ethiopia crop productivity increased by as much as 30% after replacing structures by vetiver hedgerows.

To illustrate, below pictures show the 'before-after' situation on degraded lands (first three projects were done by Habtamu Wubshet, in connection with the Ethiopian NGO 'Sustainable Land Use Forum' SLUF and with GIZ funding):

Photo 1 a & b: May 2003 - Oct. 2004 (Ethiopia, Magera)
Photo 2 a & b: Feb. 2004 - Oct. 2005 (Ethiopia, Kanat)
Photo 3 a & b: June 2005 - Oct. 2005 (Ethiopia, Kanat)
Photo 4 a,b,c &d: Feb. 2010 - May 2010 - no date (La Plantation Bemasoandro, 2010) (Madagascar).
Photo 5 a & b: same source.






15/02/2010



2. *Increasing biomass, boosting a more bio-diverse organic productivity it its vicinity*, as it supports rehabilitation of vegetation through reduced runoff and improved water retention, for example:
   a. supporting re-vegetation of mining sites, polluted or otherwise degraded areas;
   b. supporting vegetation (or even farming) on infrastructure slopes e.g. roadsides and gullies;
   c. boosting production (biomass) on-farm.
3. *Off-site impact*: with a more bio-diverse organic productivity, and its extensive, deeply penetrating root system (that also penetrates hard layers) there are also these benefits:
   a. increased ground water recharge along vetiver's copious and deep roots, which supports increasing organic productivity further down in a catchment; this happens when groundwater resurfaces in wetlands, or is used for irrigation, as well as when better groundwater storage reduces farm crop and infrastructure flood damage (we need to intensify crop production to avoid expansion of farm areas into natural vegetation); let's call this *catchment carbon benefits*.
   b. by preventing soil erosion vetiver prevents soil organic carbon from being eroded and oxidized downstream, preventing its addition to the atmosphere.

In Ethiopia trials with contour hedges on farm land showed that in the 3rd year runoff (in comparison with that of bare land) was reduced by 88% and soil loss by 97%. In that year (2003) soil loss was reduced to 3.66 t/ha whereas in previous two years (when the hedge was not yet fully effective) soil losses were, respectively, 86.3 and 48.1 t/ha.yr. So the difference is some 80 t/ha.yr even when comparing coffee farms with or without vetiver. Farmers say that where they have 20 years old hedges there is virtually no soil loss or water runoff (Kebede, 2004).

c. Improving infiltration and reducing soil loss also mitigate storm and flood damage to infrastructure.

In a country like Kenya the *mainstream* extension message is till that farmers should use the rigid engineered structures to reduce runoff; these structures ('fanya juu') indeed slow down water and increase infiltration above the structure, but with heavy rains they accumulate too much water, and the excess water is diverted to the side of the farm, where it runs off in a more concentrated (and devastating) manner. Anyway, after so many years of promoting only this 'mainstream' extension message, adoption of the labour-intensive structures is poor, maintenance even poorer.

Yet these are the problems (ICRAF, 2004):

- A total of 3.2 million t soil was washed into L. Victoria since 1963 (equivalent to one million truckloads)
- In Nyando river basin: US $42.7 millions worth of soil is lost every year (based on US $12/t) – *value 2005?*
- > 50% land abandoned due to soil nutrient depletion
- Kenya: annually lost soil value 3-4 times higher as annual income from tourism!

Add to this the impact that floods and landslides have, every year, on hundreds of thousands of in Kenya alone (and that includes dozens of human casualties, loss of livestock, homes, etc.).

Some of this could certainly be avoided, had the extension system looked more critically at the content of its message as well as the reasons why adoption is so poor. The writers' own field study on the matter, in Machakos, Busia, Samia, Kerio Valley, Kisii, around L. Elmenteita and L. Naivasha and other areas, reveals two things: i) when farmers are given a well informed choice, they choose Vetiver; but ii) most of the formal extension apparatus poorly informs farmers about VS, and their own lack of understanding perpetuates two critical misconceptions, that are: 1. *animals do not eat vetiver* (they do very well but it needs to be known that they only eat fresh leaves, vetiver is not suitable for making hay) and 2. *vetiver is planted on top of the structure* (in that way it is wasted as it does not form a semi-permeable hedge).

Farmer Participatory Research by CIAT in SE Asia (Vonkasem, Klakhaeng, Watananonta, & H.Howeler), involving more than 850 farmers, revealed that cassava producers preferred the combination of contour ridging with vetiver, among half a dozen alternative choices. In the first year the impact of vetiver is negligible but the second year the use of vetiver contour hedges did better, reducing soil loss between 0.4 and 18 t/ha, compared to alternative practices of soil and water conservation.

Other sources report reduced soil loss of between 1.3 and 143 t ha^{-1} (Greenfueltech).

There are a number of examples of crops in which the below-ground biomass does contribute significantly to SOC (sequestration), including plants such as *Andropogon gayanus* (Fisher et al., 1994), *Miscanthus* × giganteus (Clifton-Brown et al., 2007; Heaton et al., 2008; Dohleman and Long, 2009; Dondini et al., 2009a, b; Hillier et al., 2009), *Panicum virgatum* (switchgrass) (Ma et al., 2000, 2001; Liebig et al., 2005; Al-Kaisi and Grote, 2007; Anderson-Teixeira et al., 2009; Collins et al., 2010) and vetiver (*Chrysopogon zizanioides* L.) (Grimshaw, 2008; Lavania and Lavania, 2009) grasses, and even sugar cane (Otto et al., 2009; Galdos et al., 2010).

Once this more-carbon-retaining vegetation finds its new balance, there seem to be no further gains, but taking a closer look at above description we see further potential:

Ad 1c: Apart from the biomass, the water decontamination is itself highly beneficial for reducing greenhouse gases: it prevents emission of CH_4 and NH_3 and N_2O.

Ad 1d: Replacing conventional engineering (using mined materials) with bio-engineering implies a clear reduction of carbon emissions through transport (replacing far away resources by locally grown resources) and by avoiding mining of materials, requiring vegetation removal.

Ad 1e: The digging up soil e.g. for contour bunds is having its own negative impact, as with ploughing a field: it causes release of soil carbon and more greenhouse gases that would otherwise be retained in the soil. *Hedge establishment does not require much digging and being permanent, trapped sediments are kept buried* so they do not otherwise oxidize (similar to minimum tillage).

Ad 2a: Degraded areas have potential for planting vetiver for biofuel, replacing non-renewable sources that emit CO_2 and more harmful greenhouse gases (CFCs, SO_2 & nitrous oxides).

Ad 2b: On-farm biomass production can be further enhanced considering that:

- vetiver mulch can be used to reduce soil temperatures, allowing higher levels of carbon storage (carbon sink) and preventing production of other greenhouse gases;
- permanent vetiver hedges maintain a better (predator) insect balance, which supports practices of conservation farming or minimum tillage that are favourable to keeping soil carbon locked up;
- vetiver's deep rooting system absorbs nitrates from lower levels in a field (that would otherwise end up in oceans, bringing the nitrates (and potassium and phosphates) back into the biomass.

Some examples of projects with a more comprehensive approach are from poor rural and mountainous areas (e.g. in Bali, Indonesia (Booth) where the focus is on poverty reduction, and vetiver is taught to school children to protect vegetable gardens on steep slopes, and gradually involve the entire community protecting roadsides, water sources and homes), and in Ethiopia (Bottenberg, 2012). More recently a more futuristic concept of using vetiver in urban areas was presented (Aglietti): it opens the floodgates to possible urban installations where vertical fields of vetiver can play a role cleaning the polluted city environment (see picture).

From sequestration to carbon capture and storage

Carbon capture and storage is a step further than recycling CO_2 as renewable biomass fuels, in which carbon-retaining vegetation is captured in the soil, and retained in a more stable, mineral form: Soil Organic Carbon (SOC) or as biochar (elemental carbon). A good overview of the different pools of carbon is provided in 'Biological Labile Carbon' (Hoyle, 2006).

Singh in his book '*A strategy for sustainable carbon sequestration using vetiver'* (2011) shows vetiver producing 30.18 t/ha.yr dry matter in comparison with lemongrass (11.07 t/ha.yr) and palmarosa (11.76 t/ha.yr). The Carbon sequestration in biomass was 15.24, 5.38 and 6.14 t C/ha.yr respectively.

Carbon sequestration of vetiver was found to be 15.42 t C/ha.y (p 9, table 1: 14.46 in the shoot and 0.78 in the root, with dry matter production of 28.62 t/ha.y in shoot and 1.56 t/ha.y in root) (Singh, et al, 2011).

Fisher (1994) states that 100-507 million t C probably is stored in grasslands with deep rooted grasses. They estimate that there are 35 million ha of these grasslands in South America. According to these data this stores 3-14 t C/ha.

A. gayanus (vetiver close relative, also a deep-rooting tropical grass) stores o.m. 53 t/ha.yr CO_2 (Chomchalov, 2003); he cites this from Noel Vietmeyer who picked this up from a CIAT publication in *Nature* in 1995 on deep-rooted pasture grasses as carbon sinks. This is equivalent to 5.3 kg/m. Comparing this Andropogon with vetiver 'whose roots are much more extensive and deeper' it is estimated that a full-grown clump of vetiver, taking up 0.5 m^2, would absorb at least 2.5 kg CO_2 /yr. But it could be more, as vetiver has a more massive and deeper root system than Andropogon *and* huge biomass above the ground; the reason for this is its mycorrhiza association.

Taranet et al (2010) observe that vetiver total biomass yield (above *and underground*) for 4 ecotypes is between 84.4 and 114.7 t C/ha. Compared to non-Vetiver grass cultivation, vetiver cultivated areas on average increase soil carbon stock by 16.35 t C/ha, whereas in non-vetiver grass cultivation area in which this parameter decreased 12.3 t C/ha. So vetiver considerably increases carbon sequestration by enhancement of soil organic carbon with subsequent reduction of CO_2 in the atmosphere.

Linking to the *Kew grass database* (Clayton et al, 2006) and vetiver publications in Google Scholar since 2009 (Chrysopogon zizanioides) provides some very interesting information. Lavania & Lavania (2009) conjecture that a vetiver hedge could sequester up to 1 kg C/m.yr (with a hedge of 0.8 m that would be 12.5 t C/ha.yr). The figure may be already high, and it still doesn't include carbon retained in trapped sediments (vetiver's *hidden contribution*: a feature not shared by other plants under consideration – see 2.1).

More research is needed to refine these for specific soil types, climates, and slopes, but it is still clear that vetiver's potential is extraordinary.

Currently there's no simple way to measure carbon uptake or conversion of vetiver:

- Lack of site uniformity, and
- Even in well-documented cases "hard numbers" can be specious.

Only counting aerial biomass gives a serious underestimate because of vetiver's very high underground biomass to aboveground biomass ratio:

- Vetiver has a regular foliar turn-over (harvested or not);
- Not trimming plants is (in most applications) also poor management.

There are specific research questions related to different applications:

- Vetiver wetlands: how much ammonia (NH_3) can be recovered?

a. Treatment of raw sewage (black water) and/or septic tank overflow, compared to of conventional water treatment method(s)
b. in slums, rural areas, refugee camps where the method replaces the 'no-sanitation' option
c. treating waste dump leachate.

- Vetiver ponds (along boundaries and on pontoons): idem?
- *Reinforcing carbon capture in reforestation* on poor (mostly degraded, inferior quality) soils: how much is the carbon capture potential?

VS contribution to carbon capture and storage in soils requires assessment of different pools of carbon in the soil, and different ways in which VS contributes to increasing those pools and avoiding reduction in others. Literature indicates that root derived soil carbon accumulation is being estimated by scientific studies across the globe under both grassland and forests, either in the tropics or in temperate areas. In most cases Vetiver System is not applied in grassland or forestry settings, but on-farm, for infrastructure protection, and for decontamination of polluted soils and wastewater.

For carbon to truly be sequestered, that is, captured and stored in the soil, it must be transformed to mineralized carbon aided by the microbial activity in the soil associated with the root zones. One of the reasons for high vetiver plant vigour is a result of its mycorrhiza association. This association is one of the reasons vetiver hedgerows produce such high amounts of biomass. Some of that biomass can result in high amounts of organic carbon added to the sequestered soil carbon pool, both from decomposition of root biomass and dissolved organic carbon exudates from roots. In addition aboveground biomass can be converted into biochar (Grimshaw, 2011) (VS biomass fuel, 2011) (Institutional cook stoves) (Alternative fuel for Haiti). This both produces energy for cooking or power generation, and an elemental carbon residue, which when buried in soils lasts many times longer than soil organic carbon, and acts to retain soil water and nutrients, increasing plant productivity (vetiver/biochar_international_team, 2013).

Under cultivation systems a very significant part of the labile carbon fraction is lost to oxidation (removed with the crop). So vetiver hedgerows, unless used for mulching as well, are not going to have much direct impact on the other 90% to 92% of the field within a cropping system. Considering the 'Vetiver System' within the context of good management of soil fertility, and increasing o.m. in the rest of the field, the hedge is only compensating for a fraction of the much larger fraction being lost soil carbon oxidation in agricultural soils between the hedges. Practices such as no-till conservation farming as being introduced to southern African countries should overcome some of the latter problem, and underscores the need for other appropriate farm practices to be associated with Vetiver System.

We need to learn a lot more about vetiver's ability to sequester carbon under different climate and soil conditions. Scientists in China, India and elsewhere would be advised to investigate vetiver's potential. US scientists are working on *Miscanthus sp.* and switchgrass because they are known high biomass North American grasses. We should be doing the same for vetiver throughout the tropics and subtropics.

Biological Nitrogen Fixation can greatly increase in soils with high organic carbon, along with P and K availability, thus reducing need for synthetic (fossil fuel requiring) fertilizer and all the fossil carbon its production generates. The ability of vetiver to retain and enhance high-carbon soils in a stabilized agricultural system is a qualitative and quantitative advantage, regardless of what farming system is used. If biochar is incorporated it is best utilized on-site.

Biochar

Biochar (old charcoal, a highly concentrated carbon compound) has recently received a lot of attention. The Economist (Biochar Could Enrich Soils and Cut Greenhouse Gases As Well, 2009) reported about the virtue of various ways of making biochar from different raw materials, and how big the benefits would be. Two major issues came to light:

1. *Beneficial effects*, when biochar is properly incorporated into the soil, would include:
   i) remains in the soil for a long time, improving soil fertility, reducing leaching of nitrate, phosphate and potassium to ground water;
   ii) Biochar containing soils release less methane and nitrous oxide than untreated soils, probably due to physical adsorption and outcompeting plant roots for ammonium, inhibiting nitrification. As methane and nitrous oxide are more potent greenhouse gases than CO_2 this effect should help combating global warming considerably;
   iii) The biochar making process creates beneficial by-products: heat, syngas for fuel and a heavy oil, which can be used as an energy source.
2. *Major concerns* were also raised:
   - Use of existing farm land, or virgin land for biochar crops
   - Tillage would release CO_2 and methane
   - Growing switch grass for biochar may do more harm than good; garden waste and forestry off-cuts are better.

More recent research on biochar is also highlighting some concerns, see http://www.wageningenur.nl/en/Expertise-Services/Research-Institutes/alterra/Facitlities-Products/Laboratories-Environmental-Sciences-Group/Soil-Physics-Laboratory/Research/Biochar.htm, it would be worthwhile to await results from that research.

Vetiver could be the best option, having all the benefits and none of above concerns:

1. Producing very high biomass, up to 130 t/ha.yr under subtropical conditions and probably higher in the wet tropics, with a high carbon content of 45%.
2. Tolerating a wide range of climatic conditions: tropical (55^{0}C) to sub-temperate (-14^{0}C as long as the ground is not frozen), drought, flood, prolonged submergence (3 months)
3. Growing vetiver grass does not compete for farmed land as it can be grown on waste land or highly degraded agricultural lands or (tolerating heavy metals) in mine rehabilitation areas or (tolerating pollutants) in artificial wetlands and ponds to treat and dispose of industrial, municipal and domestic wastewater
4. As a perennial crop, there is only minimal release of greenhouse gases due to tillage.

Capturing dissolved ammonium from waste water

As with biogas, also the use of vetiver for treatment of wastewater deserves more serious attention. When capturing dissolved ammonium from waste water (to outcompete nitrifying bacteria that are a major source of N2O, and pumping oxygen from roots into the water, it creates a habitat for methane oxidizing bacteria. For a reference on this, see (Singh & Kalha, 2009).

Conclusion: More Research is Needed

Much more fieldwork is needed to fully quantify the benefits of vetiver. Technologies, methodologies, and algorithms need to be improved to allow measurement of Carbon sequestration, and Carbon capture and storage by vetiver. This requires observations under different climate and soil conditions, as well as different applications of Vetiver Systems. India and China are well placed for this, having some good research institutions and a wide range of growing conditions. Here are more general questions:

1. Plug in vetiver in overall data structure developing on grasses; for example there is an increasing amount of work done on carbon sequestration, but the focus is on Miscanthus. Comparative research could be an efficient way to establish the relative contribution of vetiver.
    a. broader research on grasses (versus trees)
    b. observational & experimental trial comparisons among candidate species and Vetiver (make practical judgments on utility of vetiver, using physiological & morphological indicators, e.g., energy efficiency, nutrient partitioning, biomass production & turnover, water infiltration).

CDM technology for which VS can be relevant:

Ref.	Methodologies Title	Options with VS, research
AMS-I.A.	Electricity generation by the user	Vetiver biomass for bio-fuel: small furnaces?
AMS-4I.D.	Grid connected renewable electricity generation	Idem – large scale (see Boucard example)
AMS-III.A.	Agriculture: keeping the soil, keeping carbon in place	SWC, mulching, reducing oxidation in soil
AMS-III.H.	Nutrient recovery in wastewater treatment	VS wetlands as secondary treatment of household waste water
AMS-III.I.	Avoidance of methane production in wastewater treatment through replacement of anaerobic lagoons by aerobic systems	Idem?

2. Adding Vetiver to (comparative) research scenarios already underway with other grasses (fairly inexpensive, short time-frame, practical):
    a. what are CH_4, N_2O, NH_3 and SO_2 absorption quantities for Vetiver (compared to other plants), in different conditions (using vetiver for different methods of: a. waste water treatment, b. infrastructure e.g. embankments of roads, railways, rivers, canals, and c. on-farm uses including mulch, fodder, etc.).
    b. root nutrient absorption and prevention of eutrophication as result of improved soil microbiology
    c. CO_2 mineralisation, for different conditions: quantities for roots and leaves.

Under current-day advanced remote monitoring procedures it might also be feasible to provide carbon credit income to other users of vetiver planting it for land protection, slope stabilization etc.

Two new methodology elements are being assessed under the Verified Carbon Standard (VCS) methodology approval process:

1. Methodology for Sustainable Grassland Management (SGM) (Li, 2011)
2. Methodology for Soil Carbon (The_Earth_Partners, 2012).

Also see 'Methodologies under development' (vetiver/biochar_international_team, 2013) and 'What is a Methodology?' about the VCS approval process (Carbon_Verified_Standards).

Jim Smyle (TVNI Chairman, personal communication) suggests it would be very useful if we had actual figures for vetiver and proposes a (relatively) simple research protocol for sampling SOC in the top 25-50 cm of areas with long-term (>5-10 years?) presence of vetiver hedgerows and adjacent sites for purposes of comparison. You basically only need a good methodology for selecting sites, a laboratory-grade scale and an oven to cook organic matter out of the samples. With a simple protocol and awards for researchers data from around the world (different conditions) could be collected.

Everything counts, but this is crucial:

- *Emphasizing the rooting depth*, with the assumption that (bioavailable) carbon from roots *below plough-zone depth* (where most out-gassing occurs, regardless whether you plough or not) became immobilized and perhaps eventually mineralized. This gives vetiver an enormous "direct" edge over other grasses that have been proposed for mass plantings. Taking an average plough zone of 20 cm deep, comparing that with a depth of some 1 metre (80% of the roots of vetiver are in the first metre, still another 20% beyond that depth) one can see the significance of vetiver's rooting system.
- The ability for new humus to form in stabilized debris behind hedges.
- Vetiver grass has both high biomass below and above ground. There has been virtually no research work carried out to quantify how much carbon is sequestered as root and mycorrhizal biomass and under what growth and climatic conditions.
- There are many genotypes of Chrysopogon zizanioides. Research in Taiwan (Wang) indicates differences as to where different genotypes store their carbon; some store more in the roots, others in the leaves and stem. Plant mass varies too. Fresh weight of plants grown from individual seeds in one year varied from 77 to 8.3 kg/plant. Other results show that vetiver is an effective CO_2 absorber in twice the CO_2 concentration level.
- *Comparisons with other plants*: if the vetiver hedge *retains 80 t/ha.yr of topsoil* that would otherwise be lost, this is perhaps the most important bonus of Vetiver System, sequestration-wise: keeping carbon in its place!

Several of the calculations are speculative, but we hope that research will prove that this ubiquitous plant will once again come up with trumps in this important area.

Taranet et al (2010) (cited earlier) show a difference of 28.5 t C ha^{-1} between Vetiver cultivated areas and areas nonvetiver grass areas, but it appears the study considers a pure stand of Vetiver and the typical few hedges in a field of annual food crops.

Suppose that in the more typical context only 5% of the field is used for vetiver hedges, then 1.5 t C/ha would be prevented from being lost (or added to soil carbon), equivalent to sequestering 5.5 t CO_2/ha.yr *by the vegetation of vetiver hedges alone.*

Taking another angle, preventing soil loss of 80 t/ha (Kebede, 2004), and taking this as equivalent to 5% of the top soil carbon (from the soil top 20 cm), 5% of 2400 t/ha (Lieu, 2007) gives 96 t SOC/ha.yr kept in place, preventing emission of 352 CO_2/ha.yr. But with this estimation it is assumed that all the lost soil is ending up in a way that it releases all its carbon (ignoring any deposit of lost soil in a way that it keeps its carbon), and in not all areas is the soil loss as high as 80 t/ha. And preventing soil loss with VS is rarely attributed to only the planting of vetiver hedges: it goes hand in hand with other measures (as part of a comprehensive zero-till package or organic farming methods).

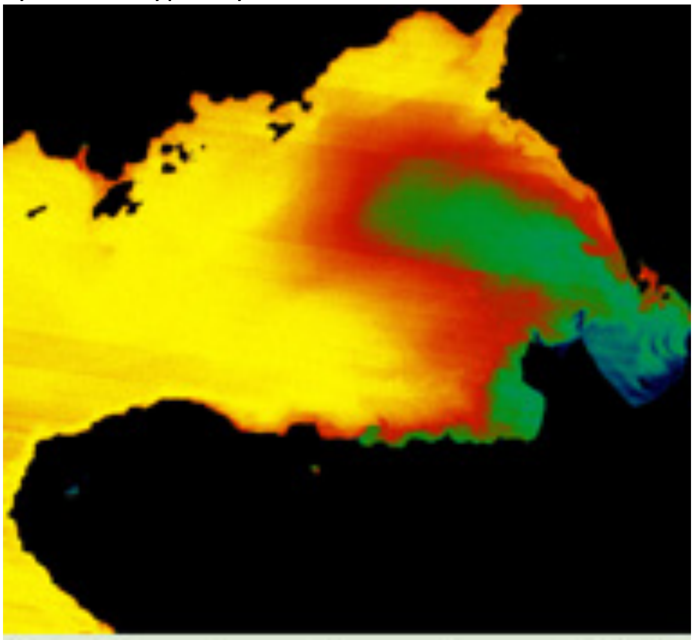
If combined with other practices it can achieve 90% reduction of soil loss. (L.Q._Doanh, et al.) but taking together a number of studies from across the world, the soil loss reduction is between 20 and 95% and it matters of course whether the study reach the 3rd year after planting; in some of these studies also reduction of water runoff is mentioned, between 40 and 80% (TVNI) (Abate & Simane, 2010?). In cases where indeed the study measures soil loss reduction in the third year, it is typically found to be over 50%.

In Kenya, soil loss on farms is about 30 t/ha in a farmed area of roughly 10 million ha (Cohen, Brown, & Shepherd, 2005). Was all that adequately protected against erosion, and assuming this would prevent emission of 30 t CO_2/ha.yr, Kenya would prevent emission of 300 million t CO_2/ha.yr (compare with US: its agricultural sector emits annually 700 million t CO_2).

The correct farming techniques can sequester carbon into the soil and reverse the 25% of Australia's greenhouse gases created by Agriculture. The processes to increase soil carbon can be divided into three steps:

1. Use plants to grow soil carbon
2. Use microorganisms to convert soil carbon into stable forms
3. Avoid farming techniques that destroy soil carbon (Lieu, 2007)

Vetiver System contributes to that in two ways: growing soil carbon and avoiding soil carbon loss.



Nyando sediment plume (green) in Lake Victoria, Feb 2000

Nyando river basin: US$42.7 millions worth of soil is lost every year (based on US$12/t, it is 3.6 million t soil yr^{-1} from 365,000 ha, or an average of 10 t ha^{-1}, (World Agroforestry Centre, 2006)

Vetiver's carbon contributions are just bonus features to its already enormous suite of positive benefits, providing individuals with flexible tools and mobilizing local resources to protect themselves from climatic fluctuations and other natural disasters, and in addition its other benefits (for pest control, fodder or materials for handicraft). This help-yourself-quality is more important than sequestration, as this is the quality that convinces the end-user.

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APPENDIX: Energy units

Quantities

- 1.0 joule (J) = one Newton applied over a distance of one meter (= 1 kg m^2/s^2).
- 1.0 joule = 0.239 calories (cal)
- 1.0 calorie = 4.187 J
- 1.0 gigajoule (GJ) = 10^9 joules = 0.948 million Btu = 239 million calories = 278 kWh
- 1.0 British thermal unit (Btu) = 1055 joules (1.055 kJ)
- 1.0 Quad = One quadrillion Btu (10^{15} Btu) = 1.055 exajoules (EJ), or approximately 172 million barrels of oil equivalent (boe)
- 1000 Btu/lb = 2.33 gigajoules per tonne (GJ/t)
- 1000 Btu/US gallon = 0.279 megajoules per liter (MJ/l)

Power

- 1.0 watt = 1.0 joule/second = 3.413 Btu/hr
- 1.0 kilowatt (kW) = 3413 Btu/hr = 1.341 horsepower
- 1.0 kilowatt-hour (kWh) = 3.6 MJ = 3413 Btu
- 1.0 horsepower (hp) = 550 foot-pounds per second = 2545 Btu per hour = 745.7 watts = 0.746 kW

Energy Costs

- $1.00 per million Btu = $0.948/GJ
- $1.00/GJ = $1.055 per million Btu

Some common units of measure

- 1.0 U.S. ton (short ton) = 2000 pounds (lbs)
- 1.0 imperial ton (long ton or shipping ton) = 2240 pounds
- 1.0 metric tonne (tonne) = 1000 kilograms = 2205 pounds
- 1.0 US gallon = 3.79 liter = 0.833 Imperial gallon
- 1.0 imperial gallon = 4.55 liter = 1.20 US gallon
- 1.0 liter = 0.264 US gallon = 0.220 imperial gallon
- 1.0 US bushel = 0.0352 m^3 = 0.97 UK bushel = 56 lb, 25 kg (corn or sorghum) = 60 lb, 27 kg (wheat or soybeans) = 40 lb, 18 kg (barley)

Areas and crop yields

- 1.0 hectare = 10,000 m^2 (an area 100 m x 100 m, or 328 x 328 ft) = 2.47 acres
- 1.0 km^2 = 100 hectares = 247 acres
- 1.0 acre = 0.405 hectares
- 1.0 US ton/acre = 2.24 t/ha
- 1 metric tonne/hectare = 0.446 ton/acre
- 100 g/m^2 = 1.0 tonne/hectare = 892 lb/acre
  - for example, a "target" bioenergy crop yield might be: 5.0 US tons/acre (10,000 lb/acre) = 11.2 tonnes/hectare (1120 g/m^2)

Biomass energy

- **Cord:** a stack of wood comprising 128 cubic feet (3.62 m^3); standard dimensions are 4 x 4 x 8 feet, including air space and bark. One cord contains approx. 1.2 U.S. tons (oven-dry) = 2400 pounds = 1089 kg
  - 1.0 metric tonne **wood** = 1.4 cubic meters (solid wood, not stacked)
  - Energy content of **wood fuel** (HHV, bone dry) = 18-22 GJ/t (7,600-9,600 Btu/lb)
  - Energy content of **wood fuel** (air dry, 20% moisture) = about 15 GJ/t (6,400 Btu/lb)
- Energy content of **agricultural residues** (range due to moisture content) = 10-17 GJ/t (4,300-7,300 Btu/lb)
- Metric tonne **charcoal** = 30 GJ (= 12,800 Btu/lb) (but usually derived from 6-12 t air-dry wood, i.e. 90-180 GJ original energy content)
- Metric tonne **ethanol** = 7.94 petroleum barrels = 1262 liters

- ethanol energy content (LHV) = 11,500 Btu/lb = 75,700 Btu/gallon = 26.7 GJ/t = 21.1 MJ/liter. HHV for ethanol = 84,000 Btu/gallon = 89 MJ/gallon = 23.4 MJ/liter
    - ethanol density (average) = 0.79 g/ml (= metric tonnes/m^3)
- Metric tonne **biodiesel** = 37.8 GJ (33.3 - 35.7 MJ/liter)
    - biodiesel density (average) = 0.88 g/ml (= metric tonnes/m^3)

Fossil fuels

- **Barrel of oil equivalent** (boe) = approx. 6.1 GJ (5.8 million Btu), equivalent to 1,700 kWh. "Petroleum barrel" is a liquid measure equal to 42 U.S. gallons (35 Imperial gallons or 159 liters); about 7.2 barrels oil are equivalent to one tonne of oil (metric) = 42-45 GJ.
- **Gasoline:** US gallon = 115,000 Btu = 121 MJ = 32 MJ/liter (LHV). HHV = 125,000 Btu/gallon = 132 MJ/gallon = 35 MJ/liter
    - Metric tonne gasoline = 8.53 barrels = 1356 liter = 43.5 GJ/t (LHV); 47.3 GJ/t (HHV)
    - gasoline density (average) = 0.73 g/ml (= metric tonnes/m^3)
- **Petro-diesel** = 130,500 Btu/gallon (36.4 MJ/liter or 42.8 GJ/t)
    - petro-diesel density (average) = 0.84 g/ml (= metric tonnes/m^3)
- Note that the energy content (heating value) of petroleum products per unit mass is fairly constant, but their density differs significantly – hence the energy content of a liter, gallon, etc. varies between gasoline, diesel, kerosene.
- Metric tonne **coal** = 27-30 GJ (bituminous/anthracite); 15-19 GJ (lignite/sub-bituminous) (the above ranges are equivalent to 11,500-13,000 Btu/lb and 6,500-8,200 Btu/lb).
    - Note that the energy content (heating value) per unit mass varies greatly between different "ranks" of coal. "Typical" coal (rank not specified) usually means bituminous coal, the most common fuel for power plants (27 GJ/t).
- **Natural gas:** HHV = 1027 Btu/ft3 = 38.3 MJ/m^3; LHV = 930 Btu/ft3 = 34.6 MJ/m^3
    - Therm (used for natural gas, methane) = 100,000 Btu (= 105.5 MJ)

Carbon content of fossil fuels and bioenergy feedstocks

- **coal** (average) = 25.4 metric tonnes carbon per terajoule (TJ)
    - 1.0 metric tonne **coal** = 746 kg carbon
- **oil** (average) = 19.9 metric tonnes carbon / TJ
- 1.0 US gallon **gasoline** (0.833 Imperial gallon, 3.79 liter) = 2.42 kg carbon
- 1.0 US gallon **diesel/fuel oil** (0.833 Imperial gallon, 3.79 liter) = 2.77 kg carbon
- **natural gas (methane)** = 14.4 metric tonnes carbon / TJ
- 1.0 cubic meter **natural gas (methane)** = 0.49 kg carbon
- carbon content of **bioenergy feedstocks:** approx. 50% for woody crops or wood waste; approx. 45% for graminaceous (grass) crops or agricultural residues.