EBI Whitepaper

Biochar-based carbon sinks to mitigate climate change

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Executive summary

The threat of climate change is increasing constantly. This is seriously bad news. And as this becomes more and more understood and accepted, the pressure on policymakers and business to act is also growing. As a result not only the European Union but also many companies have set themselves the goal of becoming climate neutral. The concept of climate neutrality means creating carbon sinks (negative emissions) whose volume is equal to that of carbon emissions.

However, the potential for carbon sinks is limited and it will take years or even decades to develop them. Moreover, since the CO_2 content in the atmosphere is already too high, it is imperative that swift and uncompromising action is taken to reduce emissions. From a technological point of view, industrialised economies have all the solutions necessary to be able to reduce their emissions by 90 - 95% in the next 15 - 20 years.

Emissions reduction alone, however, is no longer sufficient to contain the climate crisis. In parallel with the reduction of emissions, a start must now be made on expanding and further developing the existing options for creating carbon sinks. The magnitude of the task is enormous: in order to achieve climate neutrality in the European Union, the volume of sinks to be created annually must increase to at least 850 million tonnes of CO_2 by the year 2050.

Three solutions: afforestation/reforestation; biochar/biomass pyrolysis; and the build-up of soil organic matter can be implemented in the short and medium term and there is no reason why they should not be expanded rapidly. They can be implemented at a relevant volume in the short term, they are cost-efficient because in spite of their costs they have primary or additional benefits and, if implemented well, they do not have a negative but in most cases a clearly positive impact on ecosystems.

Biochar/biomass pyrolysis is thus a key technology for saving the climate. Biochar has been intensively researched in recent years. A wealth of experience with its applications and innumerable scientific publications prove today that in addition to its direct climate benefit as a carbon sink, biochar can be used in agriculture in many profitable and beneficial ways. Biochar can help to increase yields, promote humus formation, increase the water storage capacity of soils and thus raise their resistance to drought, and reduce greenhouse gas emissions such as methane and nitrous oxide as well as nitrate leaching.

For carbon sinks to be created on the scale that is necessary, a carbon sink economy with appropriate financial incentives is needed. It is crucial that robust systems are developed that are auditable, that reliably avoid double counting and that map the durability of carbon sinks and thus the actual climate impact with scientifically sound calculation methods.

The good news is that with determined and targeted action, it is possible to prevent a fundamental climate crisis by reducing emissions and creating carbon sinks. So, let’s get going.

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Key terms

Biochar: A porous, carbonaceous material produced by pyrolytic carbonization of biomass.

Carbon sequestration: Process of capturing and storing atmospheric carbon dioxide.

Carbon sink: Reservoir that temporarily or permanently absorbs and stores carbon.

Pyrolysis: Thermochemical conversion of organic compounds, particularly biomass, in an oxygen-limited environment at high temperatures.

List of abbreviations

CH_4	Methane
CO_2	Carbon Dioxide
EBC	European Biochar Certificate
Gt	Gigatons
IPCC	Intergovernmental Panel on Climate Change
NDCs	Nationally Determined Contributions
NETs	Negative Emission Technologies
NO_3	Nitrate
N_2O	Nitrous oxide
PyCCS	Pyrogenic Carbon Capture and Storage
SDGs	Sustainable Development Goals
SOM	Soil Organic Matter

Foreword

Scientific and public interest in biochar began to grow at the beginning of the 2010s and has developed considerably since then. The original focus of biochar research was on Terra Preta and soil improvement but it is now clear that this singular focus on below ground uses of biochar was unnecessarily restrictive. There is a much wider range of applications for biochar, including in industrial and construction contexts. But it is also now understood that the use of biochar in agriculture is far more complex than was initially assumed since a great many factors influence crop response. Biochar is clearly not a panacea that will bring increased yields to all agricultural crops, in any type of soil, using any application method or rate. However, we do know that there are agricultural applications in all climate zones in which biochar can offer great ecological and economic added value. This does not only mean increasing yields, but also counteracting the loss of humus in the soil, preventing nitrate leaching and improving water storage capacity and thus resistance to drought. The use of biochar in urban trees has proven to be an effective means of counter-acting increasing climate-related stress. The question is no longer whether biochar functions as a soil con-ditioner, but where and how it has the greatest effect and where its use makes the most economic sense. Beyond this, more and more applications of biochar are emerging outside agriculture.

Above all, however, it is becoming increasingly clear that we cannot do without the production and use of biochar when it comes to climate protection. Due to the level of CO_2 already accumulated in the atmos-phere, it is no longer sufficient to simply emit less CO_2. If we are to achieve the Paris climate targets and limit the increase in global temperature to well below 2°C, we urgently need the massive and rapid build-up of carbon sinks or so-called negative emissions, which capture and store carbon from the atmosphere. Biochar is one of the few proven solution options with significant potential, which, if used properly, can also provide a wide range of additional benefits in addition to carbon sequestration. The use of biochar has an evidently positive effect on the outcome of many of the United Nation’s Sustainable Development Goals (SDGs). In this document we show that biochar can make a significant contribution not only to mitigating climate change but also to developing more sustainable agriculture. But anyone who believes that biochar can solve the problem of climate change as a "silver bullet" in one shot will be disappointed: Biochar alone will not save the planet and certainly not if it is not accompanied by a massive reduction in emissions.

There is, however, another aspect: carbon and carbon compounds nowadays are not only energy sources but also important raw and primary materials for industry. With the necessary phase-out of the fossil en-ergy industry, many of these raw materials and supplies required by industry will no longer be available in the future or will no longer be available at today's prices, especially if the associated CO_2 emissions are appropriately priced. This is a further area in which biogenic carbons can provide new perspectives.

In the last 10 years there has been rapid development of both research and development activities as well as practical applications for biochar. These practical applications and methods have developed considerably as a result of the experience gained and lessons learned. Anyone whose knowledge and expertise of biochar is based on scientific research from 5 years ago or longer and has not kept up to date with recent developments is excluding up to 80% of the knowledge available today.

This whitepaper, initiated by the European Biochar Industry Consortium EBI, focusses on the climate issue aspect of biochar, i.e. the need to create carbon sinks and the opportunities that the use of biochar offers for climate protection. It will also address other crucial features of biochar, in particular significant environmental aspects other than direct carbon storage and discuss the various benefits of applications of biochar. This paper is based on extensive research on current scientific work on climate change, negative emissions and biochar. Its aim is to encourage a wide range of interested readers to look at biochar from a variety of perspectives and to rethink carbon cycles. In particular, the paper is aimed at:

- **Decision-makers in politics or in local authorities** looking for solutions to urgent issues in the context of climate change or the degradation of soils used for agriculture.
- **Journalists** and others working in the media **and environmental organisations who have** come across the subject of biochar and want to get an up-to-date picture.
- **Investors** considering investing in the fast-growing biochar market and **people** thinking about pursuing a professional career in the biochar sector.
- **Farmers** and **gardeners who** either already use biochar and have learned about its effects in practice, or are considering using it.
- **Scientists** researching individual aspects of biochar or climate change or negative emissions and would like to learn about the broader context of the subject of biochar.
- **Anyone who cares about** climate and environmental protection.

We would like to express our sincere thanks to all those whose input, criticism, viewpoints and contributions to discussion have helped us to hone the arguments and reach conclusions in this white paper.

Hansjörg Lerchenmüller

Freiburg, October 2020

1 The need for carbon sinks

Climate change is the central threat to life on earth as we know it today. It has long since become a tangible reality for almost everyone and is no longer just an abstract theory of climate scientists. The importance of climate protection has thus entered the consciousness of the European population and has ultimately led to it becoming an important political issue in many countries of the world, and especially in the policy of the European Union (EU). At the end of 2018, the EU declared the political goal of achieving climate neutrality by 2050, and in 2019 both the European Parliament and the European Council endorsed this goal. At the beginning of 2020, it was announced that it would also be enshrined in law and a proposal for corresponding legislation has already been submitted (EU, 2020). The EU's goal of making Europe the world's first climate-neutral continent by 2050 is considered the core of the European Green Deal.

At the same time, climate protection has also become an important issue for companies, corporations and not least for the whole financial sector. In order not to jeopardize access to capital markets, good supplier qualifications and, ultimately, employee and customer goodwill, companies today must put forward a credible and ambitious sustainability strategy. Whether such a path is taken out of a sense of responsibility towards future generations or because of concerns about losing competitiveness is more or less irrelevant. What is critical is that climate-responsible action becomes established, the emission of greenhouse gases is no longer taken for granted and that more and more politicians, corporate leaders and private individuals are genuinely concerned about doing what is within their sphere of influence to prevent a fundamental and irreversible climate crisis. More and more companies today have not only a sustainability strategy, but also a dedicated plan to achieve climate neutrality. In the last year and a half corporations seem to have begun to compete with each other over the announcement of climate neutrality goals. But how these goals are to be achieved in concrete terms is less clear. Tree planting projects are frequently staged in a way to best garner public attention, simply because everyone at least understands that a tree binds carbon. The removal of carbon from the atmosphere and its storage over a longer period of time is what geoscientists call a carbon sink. However, the complexity involved in this process in order for it to be effective is often underestimated or is more or less purposely obscured by scientifically unjustifiable simplifications.

Two fundamentally different lines of action are required to achieve climate neutrality: on the one hand, reducing carbon emissions, and on the other, creating carbon sinks. Let us first look at the emissions reduction side. The good news is that humanity already has all the solutions needed to quickly phase out fossil fuels such as lignite and hard coal, crude oil and gas. Numerous studies and model calculations show that a 95% reduction in energy-based greenhouse gas emissions by 2050 compared to 1990 levels is technically and systemically feasible for industrialised economic areas. For Germany, for example, it has been shown that energy-related emissions can be reduced by 90 - 95% even as early as 2035, albeit necessitating higher costs and more radical behavioural changes leading to lower energy consumption (Fraunhofer ISE, 2020). In addition to energy-based emissions, however, process emissions from industry must also be considered, for example in the production of concrete or steel. Emissions from agriculture, especially methane emissions from livestock farming and nitrous oxide emissions from agricultural soils as a result of nitrogen fertilization will also need to be curbed. These emissions can also be reduced by appropriate processes and practices, although certainly not to the same extent as is possible for energy-related emissions. Land management can also generate CO_2 emissions from the decomposition of soil organic matter. In particular, further conversion of grassland into arable land and the drainage of bogs should therefore be avoided as far as possible. The following exemplary scenario for emissions in the European Union illustrates the dimension of the remaining residual emissions. If all energy-related emissions are reduced to 10% of 1990 levels by 2050 and the historic annual reductions in non-energy-related emissions are doubled through increased efforts, the result is that, in relation to the 1990 reference value, around 15% of emissions will still remain (the authors' own rough calculation, see Figure 1).

Thus, in order to achieve climate neutrality in 2050 in this scenario by means of strong emission reduction, as proclaimed by the EU, the amount of carbon that would need to be sequestered would be in the order of 15% of 1990 emissions, that is roughly 850 million tonnes of CO_2 equivalents.

Imported and exported emissions due to global supply chains must also be taken into account in order to achieve overall climate neutrality. The European Union currently imports about 700 million tonnes of CO_2 net from trading goods and services, which are emitted outside the EU (EU, 2/2020). It is crucial to consistently include this accounting aspect, especially if there are CO_2 price imbalances¬ between different economic areas, in order to ensure a level playing field.

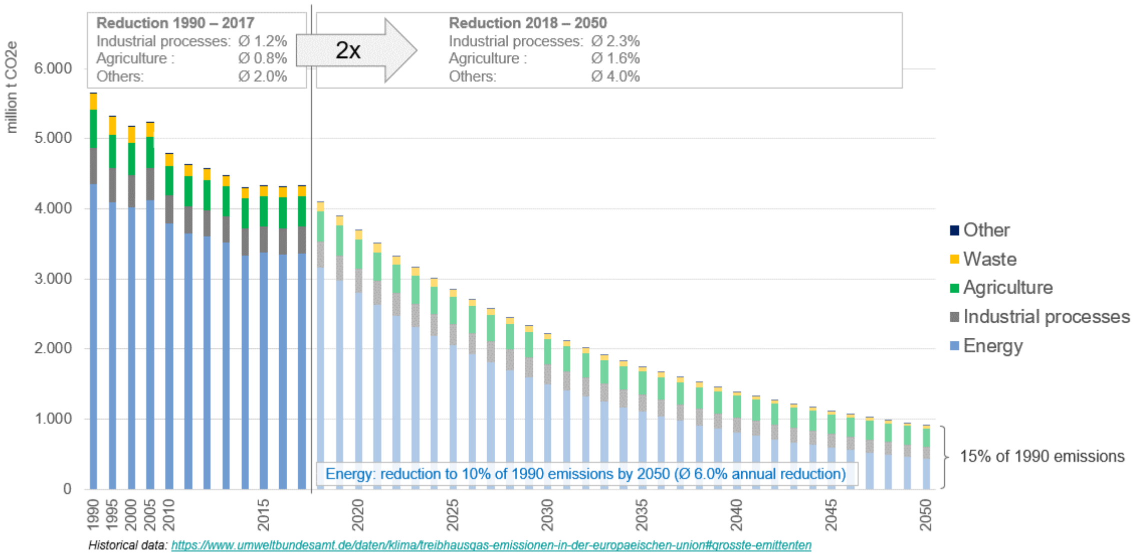

Figure 1: Historical emissions of the European Union (EU28) with reduction scenario. Scenario assumptions: Energy-related emissions are reduced by 6% per year from 2018, so that by 2050 they fall to 10% of 1990 levels. For non-energy-related emissions, the reduction effort is doubled. The result is 15% of 1990 emissions. Climate neutrality therefore means creating carbon sinks on this scale at the very least.

The challenge of an annual target of 6% reduction comes into perspective when compared to the barely 1% reduction achieved in the EU between 1990 and 2017. Precisely because emission reduction targets must be ambitious, politicians often try to find a way out of a consistent emission reduction policy by focusing on carbon sinks. But this is not working either, because at present there is no indication that sufficient sink potential can be tapped quickly enough (Nordhaus, 2019). This makes it clear: unless emissions are reduced across the board and without compromise, climate neutrality is an unrealistic goal.

If climate neutrality is reached at a single point in time, such as the year 2050, this will be a major milestone. However, this would only be a first step and there will still be a long way to go. This is because the CO_2 content of the atmosphere is already over 410 ppm (parts per million) today and will continue to rise until a balance has been achieved between annual emissions and carbon sinks. Thereafter, it will still be necessary to remove carbon from the atmosphere and store it safely far in excess of the level of residual emissions in order to lower the levels of CO_2 in the atmosphere.

The interaction of emission reduction and the creation of carbon sinks, as well as the need not just for one but for both, is clearly illustrated by the graph over time. The animated graphics of the Norwegian climate scientist Glen Peters show this in a particularly vivid way (Peters, 2018).

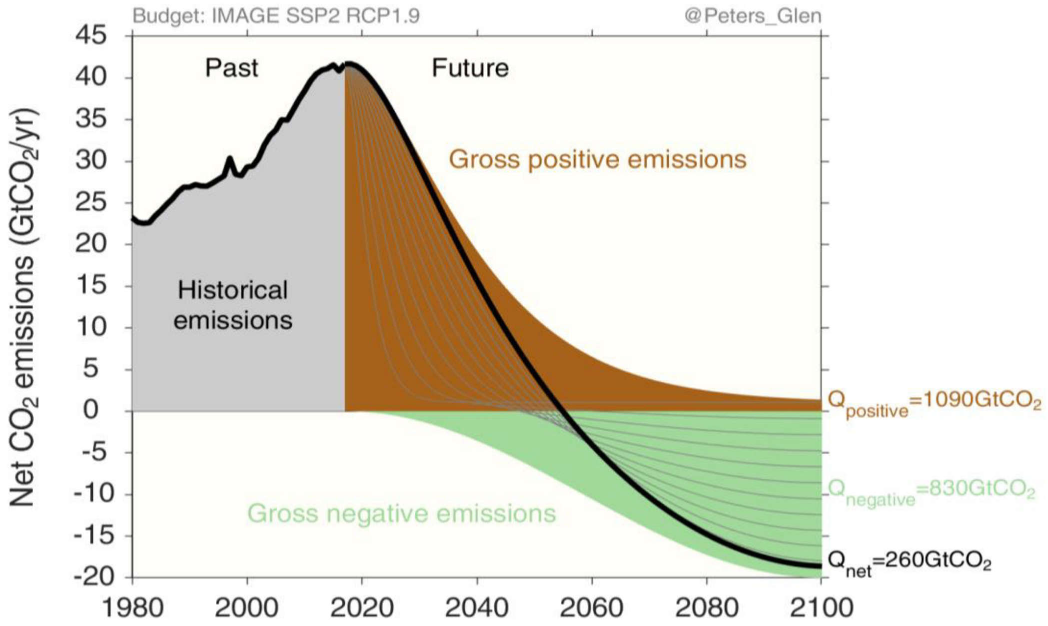

Figure 2: Historical and future CO_2 emissions in an IPCC scenario (RCP1.9) in which the Paris climate target can be achieved by a combination of rigorous emission reduction and massive build-up of carbon sinks. The brown curve shows the path of emission reduction, the green curve the path of sink build-up. The light grey lines correspond to alternative paths where even faster emission reduction would lead to a reduction in the build-up of carbon sinks necessary to achieve the climate target. In this scenario the sink capacity must already increase in the year 2050 to about 10 Gt CO_2.

Without carbon sinks, also known as negative emissions, climate neutrality and thus the Paris climate goals cannot be achieved. Carbon sinks have long been part of most IPCC scenarios and are already included in principle in the EU's climate protection plans. Even if all possible emission reductions were consistently implemented, without negative emissions the temperature rise would exceed the climate targets defined by the global community. This in turn would destroy the basis for a peaceful world, for prosperity and for a future worth living for future generations. Carbon sinks are necessary to secure the Paris climate protection goals but must not be a substitute for ambitious emission reductions. For this reason, it is essential that emissions and CO_2 sinks are treated separately and are budgeted and balanced accordingly. This also applies explicitly to corresponding emissions markets, such as the European emissions trading scheme and the national reduction targets, the so-called Nationally Determined Contributions (NDCs).

There is no alternative approach other than creating carbon sinks while simultaneously reducing emissions. From a climate science perspective, the goal is clear: we urgently need a roadmap with clear targets to create carbon sinks at a volume of at least 15% of 1990 emissions throughout the EU by 2050 at the latest. Verifiable, safe and long-lasting carbon sinks must be implemented alongside emission reductions. Only in this way can climate neutrality become a reality, only in this way can a major climate crisis be prevented.

2 Negative Emission Technologies

There is a range of viable methods of creating carbon sinks, also known as Negative Emission Technologies (NETs), that actively remove CO_2 from the atmosphere. While removal of carbon from the atmosphere is important, what is crucial for carbon efficiency is sequestration (i.e. storage) over as long a period of time as possible. The principles of carbon sink accounting are comparable to energy accounting in physics or financial accounting. In practice, however, accounting for carbon sinks while taking the system boundaries into account is often challenging, and can be time-consuming and complex. In response to this it is crucial that calculations are transparent, clearly documented and appropriately controlled. And yet current carbon sink accounting practices often lack clearly defined standards, especially with regard to the permanence of the sink. Overly simplistic calculation approaches are sometimes chosen and as a result the calculated sink performance may not stand up to scrutiny under scientifically sound assessment standards. Carbon sinks that do not deliver what they promise are dangerous. If politicians and the population feel safe because of make-believe carbon sinks, initiatives that are urgently needed to tackle climate problems will be hindered.

The concept of negative emissions attracted increased attention after the publication of the IPCC's Fifth Assessment Report (IPCC, 2014) which led to a significant intensification of work on this topic. Some of the early reviews on negative emissions still include technologies that on closer examination have been found to be impractical, risky or to have low potential. Ocean fertilization, for example, is still frequently found in the relevant overviews, even though there is now a broad consensus in the literature that this is not a viable option to pursue (Fuss et al, 2018). In the meantime, numerous publications and studies are available that provide appropriate and clear definitions of the relevant system boundaries, interfaces and interactions. This means that there is now a solid basis for a well-founded overview of existing NETs and the opportunities and risks associated with the individual solutions and also showing the limits of what can be achieved by negative emissions (IPCC 1.5°#2, 2018; IPCC 1.5°#4, 2018; EACAC, 2018; Fuss et al., 2018; Smith et al, 2019).

According to the current state of technology and science, there are six negative-emission technologies (Figure 3) that not only have sufficient potential for sequestration under current or foreseeable economic conditions, but also have a risk profile that is at the very least manageable in terms of its ecological impact.

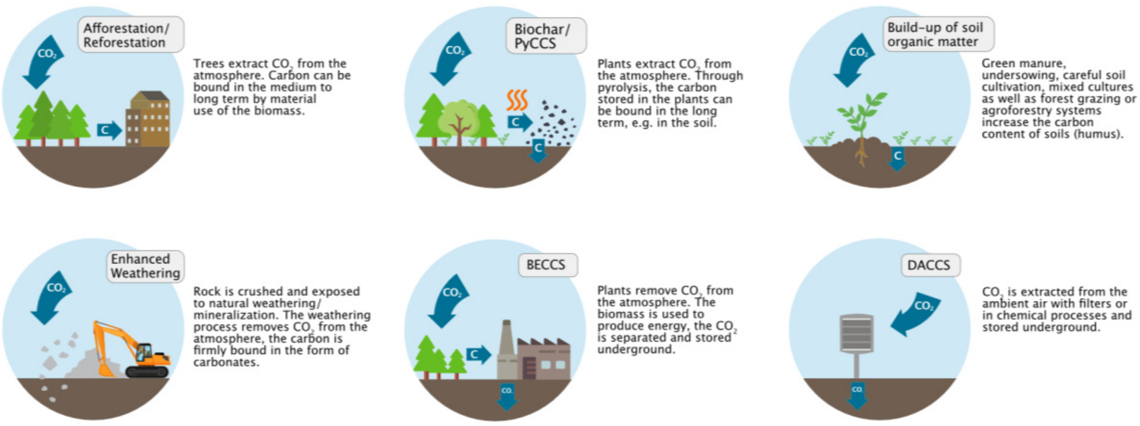

Figure 3: Overview of the six negative emission technologies that can be considered today as the most promising options for the creation of carbon sinks. Modified graph from (SRU, 2020) from which ocean fertilization and fossil CCS technology has been removed.

The development of a master plan for the creation of carbon sinks on a scale necessary for the mitigation of climate change is an urgent albeit herculean task. Policymakers must tackle it quickly and as a matter of priority, because even if it is technically feasible, the socio-economic and political aspects to be taken into account are ultimately crucial to success.

While it is tempting to develop strategies for each of the individual NETs they should not be considered in isolation. In some cases there may be competition between the different NETs when it comes to the use of resources, such as such as land or biomass. At the same time there is enormous potential for synergies, for example between afforestation and the build-up of Soil Organic Matter (SOM), or for the joint use of biochar and volcanic, siliceous rock flour to capture carbon by means of enhanced rock weathering (Amann & Hartmann, 2019). While the consideration of synergies may significantly increase the complexity of the situation, it also opens up new opportunities and paths of action.

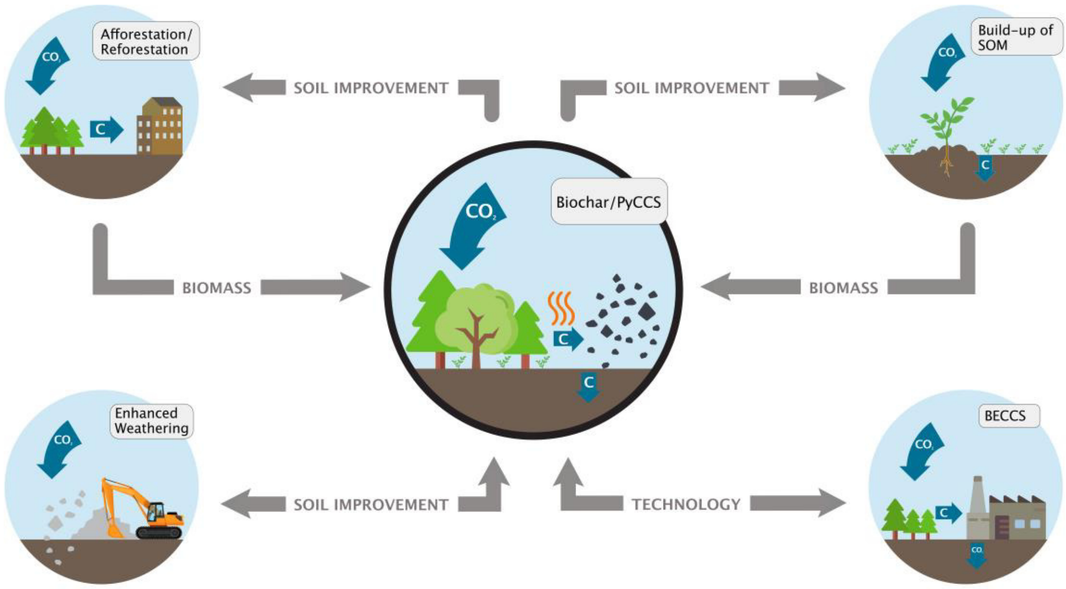

Figure 4: Synergies of biochar with other NETs.

The following are some fundamental considerations that should guide procedures and prioritization in the development of carbon sinks:

- Diversification: From a risk minimization point of view, it makes sense not to focus on just one or a very small number of Negative Emission Technologies. Due to the undeniable need to create carbon sinks, it is necessary from today's perspective to promote and further develop at least all the options shown in Figure in a targeted manner. In addition, the implementation and volume scaling of the individual solutions involve different time horizons in each case. The development of cost-effective solutions for direct air capture, for example, will probably take decades, while afforestation projects or the creation of biochar-based carbon sinks can be implemented quickly. Over time, climate conditions and economic priorities will also change and therefore it is not possible to determine without doubt which solutions are best. We also need to be able to change course when new knowledge is gained without having to start from scratch.

- Sink potential/scalability: It is vital that a solution is actually scalable and can reach a relevant and realistic sink volume. Each of the solution options shown in the Figure have their own individual sink potential, which in the current literature is usually estimated at 1 - 5 Gt CO_2 per year by 2050 (IPCC 1.5°#4, 2018). Even individually, but especially in combination, these solutions show a relevant potential.

- **Modularity:** The modularity of the solution, i.e. the question of whether an implementation can only be realized on a large scale or also on a small scale, must be taken into account. A look at the success story of photovoltaics, for example, shows that it can be of great advantage for rapid scalability if the modularity of the solution allows for both large-scale and small-scale implementation.

- **Rapid feasibility and maturity of the solution:** The development of relevant sink volumes requires time. If we want to achieve climate neutrality in Europe by the middle of the century, we must start today to push ahead at least with market-ready solutions which can be considered low-risk or which have predominantly positive side effects ("no-regret" solutions). The question of how quickly a solution can be scaled up and how mature it is, especially with regard to the assessment of risks, must be an important criterion for determining the setting of priorities and roll out timing.

- **Exploiting local potential:** While climate protection and CO_2 are global issues, the day-to-day, year-by-year work of rebalancing carbon is to be achieved at local, regional and national levels. A complete or predominant outsourcing of the task of creating sinks to other countries and regions can not be expedient. This is the case not only because of locally limited land and resources, but also because the political and socio-economic impact of import solutions, especially on developing and emerging countries, may not be reliably predicted and local political changes can lead to the rapid destruction of previously created carbon sinks. This is a particularly high risk for afforestation projects, which are not inherently stable carbon sinks. This means the basic principle has to be to sensibly exploit the potential available in one's own country. In addition, it is important that the industrialized nations should develop technical and socio-economic safety barriers.

- **Carbon-efficient use of biomass and cascading uses**: Whenever resources are limited, efficiency should play a decisive role. Biomass can either be fully combusted for energy generation or used to create a carbon sink. Carbon efficiency must therefore always be taken into account when creating sinks. "You can't have your cake and eat it", as the saying goes, and in the case of biomass, this means that it can either be burned or used to create a sink but not both. One could take the proverb a step further and say "you can't eat your cake twice" to express the fact that biomass can only be converted into a sink either through material use, or the build-up of SOM, or biochar[2] or a BECCS system. So ideally carbon sinks should be created using synergy or carbon cascade methods which begin by using material over decades and end with the creation of permanent carbon sinks. An example of this is to convert wood waste or other organic material into biochar, then to use this biochar to filter wastewater from a food processing plant thereby enriching the

[2] Biochar has a double synergy effect: it supports the build-up of soil organic matter (humus) and also enables an increased biomass build-up on more fertile soils.

biochar and cleansing the water, and then to use the saturated biochar as a slow release fertilizer or fertilizer component, e.g. combined with rock dust, which also binds CO_2 by decomposition.

- Protection of ecosystems: Negative impacts of carbon sinks on ecosystems can be significant if used inappropriately. It would hardly be acceptable if extensive sink creation were to be massively detrimental to biodiversity, or if it were to lead to other high risks to ecosystems such as increased water consumption, which could ultimately be at the expense of food production. Against this background, the cultivation of biomass in monoculture afforestation projects, especially if they require irrigation, must be avoided where possible. Carbon sink solutions (and, where appropriate, their remuneration) should always lead to an appreciation of ecosystems and their performance, not to a devaluation. This should be ensured by appropriate governance approaches.

- Costs and added value: The costs of creating different types of carbon sinks vary greatly. In the case of negative-emission technologies, a fundamental distinction can be made as to whether the sole purpose of a solution is to create carbon sinks, or whether it provides for additional benefits (e.g. yield increase and improved drought resilience in agriculture). NETs with such additional benefits should be prioritized, especially in the short and medium term. This is particularly important if this primary application also helps to reduce the overall cost of carbon sinks.

Taking the above-mentioned criteria into account and looking at the current state of knowledge, BECCS turns out to appear problematic in a number of aspects. Moreover, there will probably be at most a limited number of suitable sites. DACCS seems very promising and extensive technological developments are taking place, but realistically, scaling to a relevant volume will take decades. Enhanced Rock Weathering is now being intensively researched and also appears very promising with considerable potential for rapid scaling. There are currently numerous initiatives for its implementation in larger field trials and for quantification of its potential that can be implemented under realistic practical conditions. Given the necessary volume of carbon sinks, it is crucial to further develop the above options now, to clarify open questions through targeted research and to find suitable constellations.

Three solutions, afforestation/reforestation, biochar/PYCCS, and SOM formation, can however be implemented in the short and medium term. There is no need to delay rapidly scaling any of these solutions. They can be implemented in the short term to provide high volume sinks, they are cost-effective because they offer additional benefits beyond sinks, and if implemented well, their effect on ecosystems are not negative, but predominantly clearly positive.[3]

[3] Additional positive effects or additional benefits are also called co-benefits.

- **Afforestation, reforestation, carbon-centred forestry and material use of wood and other biomass:** Afforestation and reforestation, including in small and micro forests and agroforestry areas, as well as the increase in the carbon content of forests in combination with an increased material use of wood, all bind carbon as the biomass grows. Forests can absorb significantly higher amounts of carbon in the form of biomass through adapted forms of management. Material use of biomass from agricultural land and agroforestry systems in long lasting scenarios such as buildings, as well as planting field margins and hedges, can also be used to a far greater extent than is currently the case to create carbon sinks. By creating appropriate incentives, the material use of biomass over as long a period of time as possible should be promoted. In the case of material use, it is important that existing carbon reservoirs continue to exist, i.e. the material use must be such that, for example, the humus content of the soil not only continues to exist but increases rather than decreases.
- **Biochar & Pyrogenic Carbon Capture and Storage:** By carbonizing biomass by means of pyrolysis, a substantial portion of carbon contained in the biomass can be converted into extremely persistent forms. Pyrolysis produces biochar and, depending on the particular technology, can also produce pyrolysis-oil or energy rich process gas (see Figure 5). The possible uses of biochar range from agriculture through macadam city tree rock substrates[4] to building materials and include many other applications (see also section 3).
- **Build-up of soil organic matter:** The content of organic carbon in soils can also be increased through the application of alternative management methods such as low or no till farming, green manure, undersown crops, cover crops, mixed crops, the use of microorganisms as well as forest grazing (Silvopasture) or agroforestry systems. In its report on the soil condition survey of Germany, the Thuenen Institute assumes that under the currently practiced cultivation methods the humus content in arable soils is decreasing.[5] This, together with the recent hot summers and their effects on agriculture and forestry, emphasizes the importance in future of changing from cultivation systems to regenerative forms of agriculture, especially with year-round land cover

Table 1 outlines the main characteristics of these three nature-based NETs. Since, on the one hand, more than one solution is needed to provide the necessary sink capacity and, on the other hand, there are many synergies between these solutions, the comparison is not about competition, but about how to create a meaningful coexistence.

Table 1: Characteristics of the three most important negative emission solutions at least in the short to medium term. Summary assessment by the authors based on the sources cited in this document.

[4] This still little known concept was developed in Stockholm by Bjorn Embrén and has since been implemented very successfully (https://www.biochar-journal.org/en/ct/77).

[5] „Humus in landwirtschaftlich genutzten Böden Deutschlands – Ausgewählte Ergebnisse der Bodenzustandserhebung“ (Flessa et al. 2018, Kapitel 6).

EBI European Biochar Industry	Afforestation, C-centered forestry, material use of wood/biomass	Biochar/ PyCCS	Built-up of Soil Organic Matter (SOM)
C-Sink creation potential	Huge potential in particular outside of Europe	Huge potential	Broad range of expert opinions from huge potential to limited potential
Cost of C-sequestration	Since all these options are not just cost cases but driven by a main benefit, a cost contribution of 50 - 100 EUR/t CO2eq can really change the business case and thus trigger a strong increase of sink creation		
Stability of the sinks	Immanent risk that the sink gets lost (burned); also climate change risk	Stability broadly accepted by science	Stable only if different land management practice is continued; also climate change risk
Quantifiability	Due to risk for stability not easy to quantify	Scientifically robust quantification methodology available	Exact quantification is difficult and costly, at least at the moment
Main/Co-Benefits	Multiple co-benefits including microclimates, water retention, ...	Multiple main/co- benefits depending on application	Improving soil health and productivity, water retention
Ecological risks and negative side effects	From very beneficial (biodiverse forest) to unfavorable (monoculture, water usage, albedo ...)	None when quality controlled and certified biochar is used (e.g. EBC)	None, increase of humus is 100% positive
Carbon efficiency for use of biomass	Long-term material use of biomass has 100% C-efficiency (for the period of use)	Today typically 30 - 60% (less critical due to energetic use of the residual amount); with use of bio-oils up to 70%	if huge amount of biomass is used for area composting C-efficiency is low otherwise it can be very high
Availability and scalability	Practices available even though scaling of larger projects can take time	Quickly scalable, technology readily available	Practical experience available. More research regarding large scale agricultural deployment required.
Use of other ressources	Land and potentially water requirement	Depending on the sustainability of biomass feedstock	No relevant use of energy and water needed

It is beyond the scope of this paper to provide more details of all six NETs. However, as the EBI is focused on biochar, and it has recently been attracting increasing attention, it is our intention in this white paper to provide both broader and more in-depth information on biochar.

3 Biochar as Negative Emission Technology

In order to grow, plants extract CO_2 from the atmosphere by means of photosynthesis. When this plant biomass is burned or decays, carbon is released back into the atmosphere in the form of climate-damaging gases, mainly CO_2. This is part of the normal carbon cycle and if atmospheric carbon levels were not already too high, this release of CO_2 would be fine.

However, if the biomass is pyrolyzed (i.e. “baked” in a low or no oxygen environment), about half of the carbon compounds of the biomass are converted into biochar. This high-carbon material is very durable and resists biological or chemical decomposition. If biochar is not burned but rather remains in the soil or is used in other long-lasting material applications, a carbon sink is created, always provided that the provision of the biomass does not diminish existing carbon stocks (EBC, 2020).

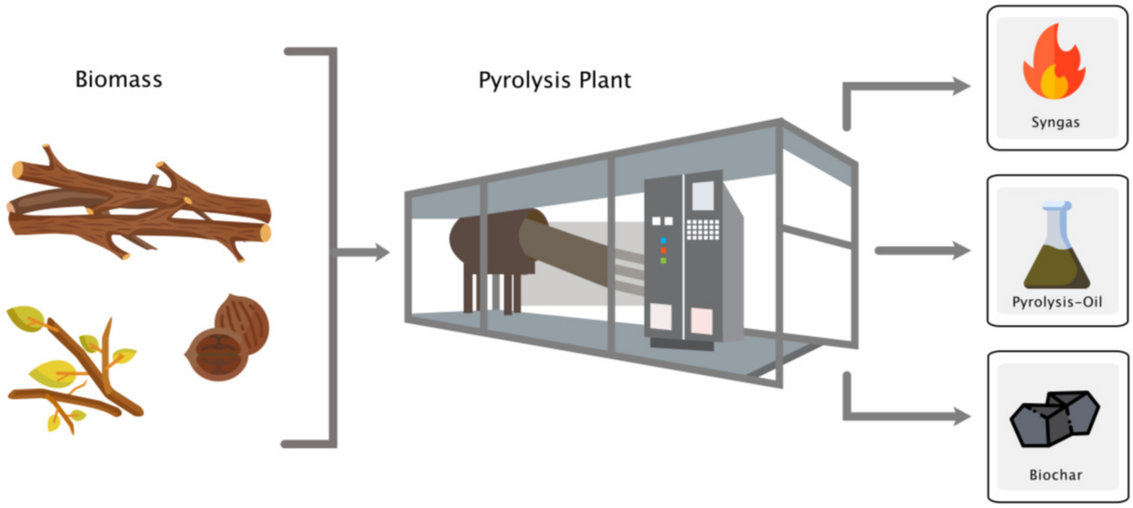

Figure 5: Material flows in the pyrolysis of biomass. Depending on the process, the distribution of the carbon contained in the biomass to the three possible end products – and thus the proportion of carbon that becomes a sink – can vary.

What is decisive for climate benefit is the overall balance of biomass production, pyrolysis, further processing and application. Only if this balance is overall positive for the climate can we speak of a true carbon sink. The European Biochar Certificate (EBC) for quality control (EBC, 2012), which has been established for several years, was augmented in June 2020 with a new standard for the certification of carbon sinks (EBC, 2020). This created a scientifically sound basis for quantifying the overall carbon sink performance of biochar applications. The most important elements include:

- Biomass production must be climate-neutral, i.e. it must not diminish existing carbon sinks. This can be ensured, for example, by using agricultural or other waste, rapidly growing biomass or other material recovered from the care and maintenance of biodiversity areas, the countryside and roadsides. Wood from sustainably managed forests can also meet the criteria.

- Emissions from the entire carbonization (pyrolysis) process must be deducted. These include, in particular, emissions related to the transport and processing of the biomass, to any treatment after the process and to the energy required to start the pyrolytic process. In modern pyrolysis plants, both the process gas and the waste heat are typically used to generate renewable energy. Due to their high climatic relevance, special attention is paid to possible methane emissions, which, however, are marginal in modern industrial plants.

- Emissions from the transportation of the biochar to the place of application and, where appropriate, emissions from further processing of the biochar must also be deducted.

- The final use of biochar determines the durability of the carbon sink. In soil applications, for example, a scientifically based annual decay must be assumed. If the biochar is used as a sand substitute in concrete, however, this is not necessary, as the biochar cannot oxidise in the absence of air. When used as a filter material, on the other hand, a permanent carbon sink is only created if it can be ensured that the filter material is deposited on a long-term basis. While it may well make sense for biochar to be used to replace fossil carbon for energy purposes or, for example, as a reducing agent in metal production, because it replaces fossil raw materials, this does not constitute the creation of a carbon sink.

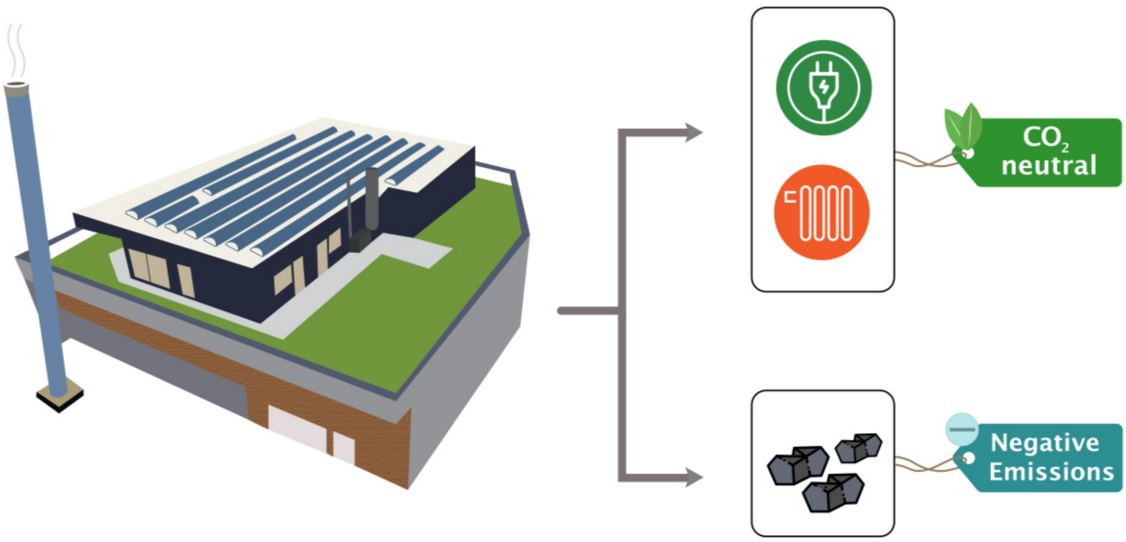

Figure 6: Environmentally friendly production of biochar with an up to four-fold value creation: (i) generation of CO_2-neutral electricity, (ii) CO_2-neutral heat, (iii) biochar and (iv) negative emissions. Plant types that are not designed for electricity generation convert a higher proportion of the initial biomass into biochar and thus into carbon sinks.

3.1 Persistence of biochar in various applications

The decisive factor for the climate impact of a carbon sink is its permanence. There are a large number of economically, technologically and ecologically sensible applications for biochar, but not all of them ensure permanent carbon sequestration in the same way. A distinction is therefore necessary.

- Applications in soil: When biochar is added to agricultural or urban soils, for example in the form of substrates, as an additive to compost or liquid manure, or via use as a feed additive, its carbon is stable for centuries. The application of biochar in agricultural soils has been discussed as a method for sequestration (i.e. binding and storage) of carbon since the beginning of the millennium (Glaser et al, 2002; Lehmann et al, 2006; Laird, 2008; Woolf et al, 2010). Since then, numerous scientific papers have dealt with the persistence of carbon in soil and have shown that the mean residence time of biochar in soil is higher than that of all other organic carbon compounds (IPCC, 2019; Lehmann et al, 2015; Wang, 2015). This ensures long-term sequestration in principle. In order to quantify the long-term persistence of biochar in the soil, however, it is necessary to extrapolate results of experiments over a few years to long periods of time and these results are subject to statistical uncertainty. The quotient H/Corg has proven to be a good explanatory variable for persistence (Lehmann et al, 2015). If it is below 0.4, an annual degradation rate of 0.3% can be assumed (Camps-Arbestain et al, 2015). A summary of global data shows that at the current stage of research this is a conservative estimate. In 2019, based on the above-mentioned scientific publications, the IPCC published a method for quantifying the decomposition of biochar in the soil (IPCC, 2019).
- Irreversible binding in materials: If biochar is incorporated into building materials in a way that precludes combustion, no degradation rate needs to be applied. Examples include applications in asphalt, concrete, lime plaster, gypsum and clay (EBC, 2020). These types of applications are being developed worldwide by various industry players.
- Reversible binding in materials: Biochar can be incorporated into industrial materials such as plastics or other recyclable materials. There are numerous research and pilot applications for this. No degradation rate needs to be applied to these applications either, but the length of time the material is in existence must be taken into account. As soon as the material is thermally recycled, for example in a waste incineration plant, the carbon sink in question is destroyed. Material recycling can also lead to the release of some of the bound carbon while some remains bound in the recycled material. The recognition of such applications as carbon sinks requires special care involving reliable and conservative statistical estimates of their service life and effective monitoring.

3.2 Potential of the sink capacity of biochar/PyCCS

Biochar and PYCCS's potential sequestration capacity depends strongly on assumptions about the availability of biomass and its allocation for the production of biochar. It is therefore not surprising that a broad spectrum of potentials has been mentioned in the literature. While some publications show worldwide annual potential of at least 3 - 6 Gt CO_2e (Werner et al, 2018; Smith, 2016; Lee & Day, 2013; Woolf et al, 2010; Lenton, 2010) other authors consider the achievable potential to be rather in the order of one Gt CO_2 (Griscom, et al., 2017). If other biomass sources such as sewage sludge and maritime biomass are included, the potential is much higher (Bates & Draper, 2019).

In addition to the question of which biomasses should be converted via pyrolysis processes, there is another aspect which is increasingly being taken into account when considering their potential: ¬ the fact that pyrolysis can be used to produce not only biochar, but also pyrolysis-oils and process gas. Process gas can be used in the chemical industry or for energy purposes while pyrolysis-oil can be used for carbon sequestration, either through material use or through geological storage (Schmidt et al., 2018). This means that carbon efficiency can be increased from today's level of 30 - 60% to up to 70%. If used in combination with CO_2 capture technologies such as those which might be used in BECCS or fossil CCS technology, even higher efficiency could be realized.

A decisive advantage in terms of rapid scaling is the modularity of the technology. In modern pyrolysis plants biochar can be produced economically using relatively small amounts of up to 1,000 t biomass (dry mass) annually or roughly 2 – 3 tonnes per day. The advantages of smaller scale production are the short distances involved in supplying the plant with biomass and the ability to use the residual heat produced locally, which is important for the economic efficiency of plant operation. Provided that suitable quantities of biomass are available locally, plant sizes of up to 100,000 t of annual biomass are also feasible, so the cost scaling effects for the production of biochar can be achieved. The more cost-effective its production, the more applications can be developed using biochar. Under the current economic conditions, biochar is used at present primarily in high value agricultural crops, in animal feed and to extend the life and resilience of urban trees. As the volume of biochar production increases and the service to the climate in the form of removing and storing carbon is increasingly and separately remunified, so the price for biochar will decrease, enabling broader applications of biochar.

Relevance of PyCCS in an exemplary calculation

A simple model calculation shows that even in a densely populated country such as Germany, a distinctly relevant sink volume can be achieved using biochar or PyCCS. The amount of wood currently harvested annually from forestry in Germany is around 68 million m^3 (Destatis, 2020), corresponding to around 37 million tonnes of wood. If a proportion of 50% were converted into stable carbon compounds either directly or indirectly via material use with a 70% carbon efficiency, the result would be a carbon quantity of almost 25 million t CO_2 equivalents[6]. Similar estimates for the carbonisation of waste and residual materials from landscape conservation and the food industry, sewage sludge, harvest residues and specifically cultivated biomass such as in agroforestry systems, marginal planting or short-rotation plantations, result in a further potential of 10 - 20 million t CO_2. Compared to Germany's current emissions of around 800 million t CO_2, this is remarkable, but at the same time seems to be rather low. Together with a 95% reduction in emissions by 2050, however, it can be seen that the volume of sinks that could be created is of the same order of magnitude as the total remaining energy-related greenhouse gas emissions.

When it comes to the question of which biomass should be used for the production of pyrolysis products, many approaches fall short and rely exclusively on the use of residual forest wood. In addition to forestry residues, many other forms of underutilized biomass can be used for biochar/PyCCS (EBC, 2020). All of them have already been successfully piloted and could scale quickly and thus should be not only seriously considered but also swiftly supported and implemented.

- Agricultural biomass includes both crop residues, which are thus regarded and enhanced as a raw material, and the cultivation of rapidly growing biomass, such as miscanthus, hemp, switchgrass and silphium.
- Organic residues from food processing or secondary uses of biomass, such as grape marc, nut shells, fruit stones, coffee chaff and coffee dregs.
- Wood from landscape management, short rotation plantations, agroforestry, forest gardens, field margins and urban areas.
- Biomass from forest management. At a minimum, it must be ensured that the volume of new growth in the forest is greater than the amount of biomass removed.
- Waste wood such as papermill and sawmill residues, as well as recycled timber from construction and demolition sites.
- Biomass and harvest residues that have to be sanitized to kill pathogens and interrupt infection chains, such as tobacco mosaic viruses in tomato or bell pepper plants in protected cultivation.

[6] 50% carbon content of wood, dry weight 0.54 t/m² and 3.664 t CO_2 per t carbon

- Other biogenic residues for which there are few or no safer management options, for example sewage sludge and liquid manure.

Clearly a paradigm shift is needed to increase the potential of creating carbon sinks from biomass. Only if the value of carbon as a sink is adequately taken into account and any emissions from the energy use of biogenic carbon are considered avoidable in the long term, can valuable biomass residues be used for what they should be used for, namely for the creation of carbon sinks. This is ultimately the application with which biomass makes a crucial contribution to climate protection, which cannot be made by classical renewable energies such as photovoltaics or wind energy in principle. The fight against climate change requires the appropriate course to be set immediately for the sustainable use of biomass carbon.

3.3 Application benefits of biochar

Carbon sequestration by capture and underground injection or mineralization of CO_2 (see BECCS) is a form of carbon sequestration that is exclusively associated with costs. In contrast to this, economic considerations of biochar always have to take into account the direct benefits derived from the application of the biochar itself. All relevant applications of biochar today are driven by their respective benefits. In the case of biochar there is therefore always both an application benefit and a climate benefit. Which of these is the main benefit and the secondary benefit (co-benefit) depends on the perspective. For example, a climate scientist calls the soil-improving effect of biochar a co-benefit. For the farmer who uses biochar as a feed additive because his practical experience with it has been positive in terms of animal health and the economic results of animal husbandry, the climate benefit is the secondary benefit.

Cost sharing between climate benefits and agricultural benefits

If, for example, a farmer buys high-quality and quality-assured biochar for 900 €/t and feeds it to his cows as a feed additive because it produces better results, then it naturally makes no sense to allocate the entire purchase costs of the biochar to the carbon sink performance. Taking all losses into account, one tonne of biochar binds about two tonnes of CO_2. So, if the farmer receives say 50 €/t CO_2 for the climate service of carbon sequestration today, this means that he will receive a good 10% of the biochar costs financed by his service to the climate. If the value of the climate service increases to say 150 €/t CO_2 in the future, this will already cover one third of his costs. As technology develops, the production costs of biochar will decrease and the balance for the farmer in future will be increasingly favorable.

The application benefits of biochar are as varied as the range of applications itself. This is especially true because in many applications biochar is used in a cascade, that is, it is first used in the barn, then the biochar migrates to the field via the biogas plant and then it remains there for centuries as a soil-improving auxiliary material.

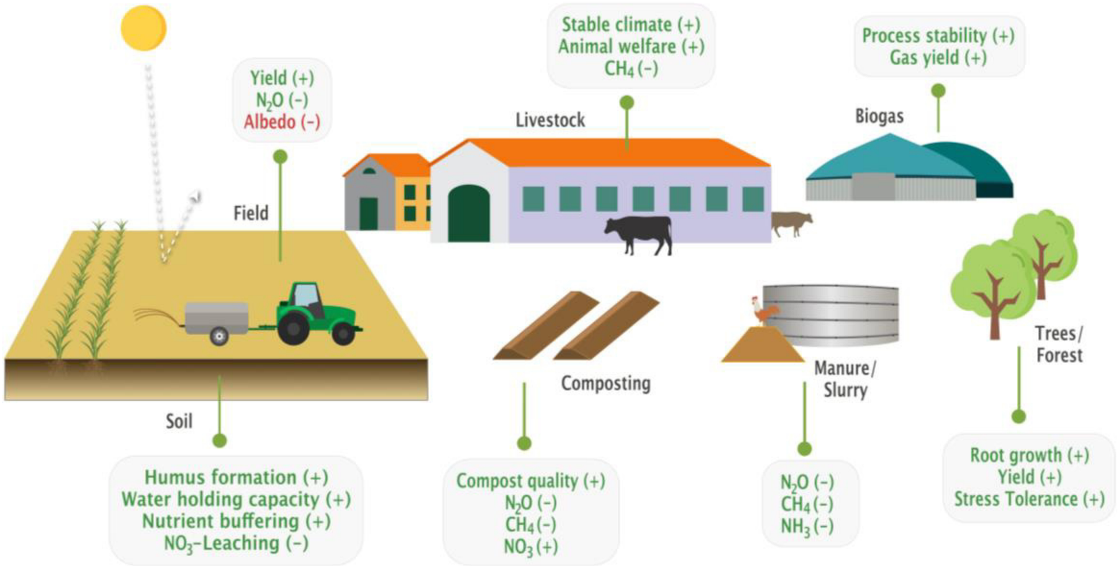

Figure 7: On a farm, biochar can be used in the following systems: stable, manure, biogas plant, composting, field, trees/forest and soil. The framed text boxes show which effects biochar has in each system. The characters in the brackets (+)/(-) show how biochar influences the respective parameter: (-) reduction (+) increase. The color indicates whether the change is positive (green) or negative (red).

There is only one side effect of the use of biochar which can have a systematic negative impact even when used properly, namely the reduction of albedo (a measure of the reflectivity of sunlight). Biochar makes soil slightly darker, which can lead to less sunlight being reflected back into space, thus contributing to global warming (Meyer et al, 2012). This is, however, a phenomenon that scientists call a "second-order effect". This is because the only concern is that a part of the positive climate effect resulting from the introduction of biochar may be cancelled out by the albedo effect. Since biochar should always be incorporated into the existing soil, the quantities currently applied generally only result in volume fractions in the order of one percent of the soil. Moreover, it is good professional practice for arable soils to be covered with plants or plant residues for a large part of the year, or better almost the whole year, and so in reality the albedo effect plays a subordinate role. Nevertheless, it should be taken into account when implementing large-scale biochar applications and minimized by appropriate application and management methods (Bozzi et al, 2015).

With regard to all other effects shown in Figure 7, there is now a scientific consensus that biochar, when used properly, leads to statistically averaged changes that can be positively evaluated (Glaser, 2018). Nevertheless, the use of biochar in agriculture is far more complex than was initially assumed and must be considered in a more differentiated way than has long been and in some cases still is being propagated today by both advocates and critics of the approach. Under no circumstances should the outcome of a single series of experiments or even a single experiment be used to form an overall judgement about biochar. Biochar can be produced from a wide variety of biomass feedstocks, at different temperatures and under widely varying process conditions, so it is hardly surprising that the use of different types of biochar leads to different results. Another crucial factor is the way in which the biochar has been pre-treated before it is used in the soil. In practically every case of soil application biochar has to be charged with nutrients prior to its application in the soil and here too there is a wide range of possibilities and variants for such pre-treatment or refinement. Last but not least, soil properties and the type of agricultural crop play a decisive role in the influence that biochar has on the multitude of parameters that can potentially be addressed. For a long time, when considering the effect of biochar, the focus was one-sidedly on yield increases. However, the added value that biochar can offer in its application in the soil, at least in optimized agricultural systems, involves not only increasing yields, but also counteracting the loss of humus in the soil, preventing nitrate leaching and increasing the water storage capacity in order to improve the plants' resistance to drought and their resilience to the climate crisis.

In the past 10 years there has been a rapid development of research and development on biochar with an exponential growth in the number of scientific experiments and publications. The scope of the work has expanded so much in depth and breadth that it is becoming increasingly difficult even for proven biochar specialists to stay equally up-to-date in all subject areas. Accordingly, specialist fields are emerging, as is the case in all growing fields of science and technology. So it is not surprising that this dynamic progress sometimes leads to biochar being criticized on the basis of arguments which are no longer up-to-date with current science and so are quite simply false or so out-dated that they are no longer relevant.

The following table provides a summary of the profitable and beneficial uses of biochar on the basis of 12 arguments. Risks and negative side effects are low or controllable if handled appropriately and are in every case overcompensated by the benefits.[7]

[7] A review of scientific papers supporting these 12 arguments in favour of biochar is currently being prepared in collaboration with leading biochar specialists and will be published shortly with further sources cited.

Table 2: Twelve good reasons for using biochar. These arguments can be scientifically well proven on the basis of the current literature.

#	Twelve good reasons for using biochar	Selected sources
1	Biomass pyrolysis is a key technology for saving the climate	(Werner et al, 2018; Woolf et al, 2010; Woolf et al, 2016)
2	The use of certified biochar has been proven to meet the highest environmental standards and, when used properly, is safe for soils, ecosystems and users	(EBC, 2012; Lehmann & Joseph, 2015)
3	Pyrolysis can be used to close organic material cycles. This is a prerequisite for the principle of recycling in the bio-economy.	(Woolf et al, 2016)
4	Biochar improves the water retention capacity of soils and, in combination with fertilizers, leads to yield increase and stabilization	(Ye et al, 2020; Razzaghi et al, 2020)
5	Biochar helps to build up humus	(Blanco-Canqui et al, 2020; Weng et al, 2018)
6	Biochar reduces GHG emissions from agriculture	(Borchard et al, 2019; He et al, 2017; Liu et al, 2018)
7	Biochar reduces nitrate pollution of ground and surface water	(Borchard et al, 2019)
8	Biochar shows multiple benefits in animal husbandry and improves animal health	(Schmidt et al, 2019)
9	Biochar promotes tree growth and increases the stress resistance of urban trees	(Embrén et al, 2016; FLL, 2017)
10	Biochar can be used as an additive in composting to improve compost quality and reduce nitrogen losses	(Godlewska et al, 2017; Zhao et al, 2020)
11	Biochar can improve the properties of concrete and asphalt	(Gupta & Kua, 2017)
12	Biochar enables the rehabilitation of contaminated soils	(BMLFUW, 2017)

4 Emergence of a carbon sink economy

In order to avert dangerous climate change, it is essential to create carbon sinks quickly and on a significant scale. And, this point cannot be stressed often enough, this must be done in addition to reducing emissions and is essential to offset the remaining unavoidable emissions. Those who perform this vital service must be paid appropriately. The creation of stable carbon sinks of 850 million tonnes of CO_2 equivalents, which is the order of magnitude necessary to achieve climate neutrality for the European Union in 2050, corresponds, according to current estimates at reasonable prices, to a market volume of EUR 80 - 150 billion. This will not succeed only on the basis of donations. Since this is a task for society as a whole, it seems sensible to consider the provision and remuneration of this service in state-regulated systems. As things stand at present, emissions taxes and emissions trading systems are particularly suitable for this purpose, supplemented by voluntary and mandatory disclosure standards for companies.

Remuneration in the context of voluntary commitments by private individuals, companies and public institutions is a crucial first step. This would mean, on the one hand, suitable standards being tested and their functionality demonstrated and, on the other hand, remuneration in the voluntary market allowing these key technologies to be advanced in a manner which is already economically viable. With these remuneration instruments, carbon sinks – and in particular the production and use of high-quality and safe biochar – can be scaled up economically in a way that makes ecological sense, is technically feasible and is thus desirable for society as a whole. From the point of view of those who remunerate sinks, this is an opportunity to promote the development of carbon sinks in addition to their own efforts to reduce emissions.

The basic standards must ensure that the service is actually delivered effectively and is correctly quantified and that, on the other hand, no environmental or social damage is caused elsewhere. This applies in particular to biodiversity, the protection of ecosystems, water resources and food security. Taking such standards into account, remuneration in the voluntary market can make a decisive contribution to climate protection.

From a macroeconomic perspective, the carbon sink economy is to a certain extent a reversal of traditional value chains in which products and services associated with high emissions are implemented. The value that is remunerated in the carbon sink economy is not created through the consumption of energy and thus through the release of carbon into the atmosphere, but the other way around, through the permanent binding of atmospheric carbon. This also shows that, although emission reduction and the creation of sinks are both necessary, they are completely different in nature: the former can be compared with avoiding waste and disorder, and the latter with cleaning, clearing up and recycling services.

Since, in this comparison, we have already produced too much waste, the recycling service is a socially and economically necessary task for the whole of society, which regardless of further pollution must be recognised economically.

4.1 Accounting principles for carbon sinks: No sink is forever

If the climate service of carbon storage is to be remunerated in a fair and accountable way, transparent and, if possible, uniform principles for its accounting are needed. To this end, it is necessary to take a detailed look at the carbon cycles and especially their time constants. If this is done, it quickly becomes clear that the burning of fossil carbon cannot be compensated simply by afforestation.

There are many reservoirs of non-atmospheric carbon, both terrestrial and marine, more stable and less stable, natural and man-made. Ultimately, all of these reservoirs are exposed to natural carbon cycles in the course of which they change and non-atmospheric carbon becomes atmospheric carbon and vice versa. Furthermore, these cycles are subject to complex interdependencies and the circulation speeds of these cycles vary considerably. Faster cycles are, for example, the annual exchange of carbon between the atmosphere and green plants, which even manifests itself in an annual up and down of atmospheric CO_2 concentrations. The growth and decay of woody biomass, forests and moors in contrast are subject to cycles of between decades and centuries or even millennia. There is also a rapid exchange of carbon between the upper ocean layers and the atmosphere and a much slower exchange between the atmosphere and deep ocean layers. Fossil carbon is a particularly stable and thus a particularly valuable reservoir from a climate protection perspective. If a certain amount of CO_2 is released into the atmosphere, about half of it will decompose within a few decades, but the remaining part will remain in the atmosphere much longer and even after 1,000 years, 15 to 40% of the emitted amount will still be present in the atmosphere (IPCC, 2/2014). This shows that the destruction of a fossil reservoir can by no means be compensated simply by creating a temporary sink of a few years, for example by planting trees, especially since these kinds of reservoirs are endangered by climate change itself (e.g. by fires as in recent years increasingly in Siberia, Australia, California and the Amazon region).

Current knowledge shows that it is necessary to exploit the potential of all the above-mentioned carbon sinks. However, they differ considerably in terms of their quantifiability, their permanence, their co-benefits and also their risks. It would therefore be a mistake to naively apply to the carbon sink economy the classic and already too short-sighted line of argumentation for emissions trading, namely to realise savings where they are cheapest to obtain.

In order to create functioning incentive systems, it is necessary to balance carbon sinks rigorously. In particular, there must be a clear assessment of carbon sinks against baseline scenarios and all emissions associated with the creation of the respective sink must be taken into account. This includes in particular the possible destruction of existing carbon reservoirs for the provision of source material and all relevant production and transport processes. In addition, the underlying assumptions must be validated, and the services actually rendered must also be verified (ISO 14064-02, 2019).

To ensure the comparability of carbon sinks, it is also necessary to take into account the sequestration curve of the amount of carbon stored over time. So, for example, it makes a considerable difference to the level of warming potential avoided whether a tree is planted that builds up and stores 1 t of carbon over 30 years and is then felled, whether 1 t of carbon in the form of biochar is stored safely and permanently in building material, or whether 1 t of carbon is built up in arable soil over 10 years in the form of humus which remains there for a longer or shorter period depending on further cultivation (see also: Figure 8).

In the case of biochar-based carbon sinks, the baseline scenario can generally be thermal utilization or decomposition of the biomass. Furthermore, financial additionality can generally be assumed, since the remuneration of sink performance is an important element for the economically viable use of biochar. After deducting all emissions that occur during the provision of the biochar, including the extraction of the biomass and the creation of the carbon-preserving application, the carbon contained in the material over time can thus be counted as a sink. The time-dependent sequestration curve thus obtained characterises the carbon sink and is the basis for the balance.

In principle, such a sequestration curve can also be used to indicate the carbon content of a forest body or the humus content of the soil. However, if the carbon growth of a forest in a designated, not too large and clearly defined area is considered a carbon sink, there are some challenges for calculating the balance and possibly also the remuneration. In particular, it is necessary to define how to deal with a possible later drop in the carbon quantity below the original starting point. Anyone who is remunerated for the carbon growth of a forest over a certain period of time would, logically, also have to pay for any loss of carbon below the starting level. However, it is unlikely that this would be enforceable, especially since the loss of the forest also represents a considerable economic loss for the forest owner. Moreover, external circumstances, such as climate change in particular, which cannot be attributed to the owner of the sink, can lead to a loss of carbon sinks. For these reasons, areas of forest as carbon sinks are more suitable for consideration in a more comprehensive, typically government-managed, carbon balance.

Similar challenges arise in the balancing of humus formation., Here the quantification of the amount of carbon in the soil is also particularly demanding and methodologically challenging, although much progress has been made recently with regard to sensors and modeling. Carbon sinks on the basis of individual and small-scale biochar applications, on the other hand, prove to be particularly suitable for balancing on a granular level. This is because the determination of the baseline scenario is comparatively uncomplicated and the quantification and tracking of individual biochar applications (e.g. according to the EBC standard for carbon sinks) can be guaranteed.

Table 3: Requirements for carbon sink credits according to the Code of Best Practice of the International Carbon Reduction and Offset Alliance (ICROA, 2020).

Request	Assessment for carbon conserving applications of biochar
Actual sink	According to the EBC-Sink Standard, sink credits are only granted for sinks already created.
Measurable	The EBC-Sink Standard ensures quantification according to the latest scientific standards. If exact calculations are not possible, conservative estimates must be used.
Permanent	Durability depends on the type of application. Accounting according to EBC-Sink requires durability to be taken into account.
Additionally	The appropriate alternative scenario is the thermal utilization of biomass. The remuneration of the sink performance is an important element for the economic use of biochar.
Independently verified	The EBC-Sink guidelines provide the basis for independent verification. The corresponding audit processes are currently being introduced.
No double counting	Depends on appropriate agreements and contracts with manufacturers and users and corresponding documentation and tracking, ideally on a block chain basis.

4.2 Remuneration of carbon sinks

A prerequisite for fair remuneration of the creation of carbon sinks is the quantification of their performance. The accounting principles outlined in the previous chapter, which involve the quantitative characterisation of sinks using a sequestration curve, appear particularly well-suited to achieving the necessary comparability of sinks. In addition, a suitable method must be found to ensure that the same sink is not remunerated more than once. A decisive point for the remuneration is the segregation of the sink performance from the physical sink itself. Through the conclusion of corresponding contracts, the right to use the sink service rendered is relinquished – but of course not the physical sink itself. In this way, a certificate can be created which securitises the claim to the sink service rendered and can be transferred from owner to owner independently of the physical sink.

The performance of the sink service can be remunerated for to the party that has performed it itself or has the corresponding contractual relations with that party. In the case of sinks based on biochar applications, this is typically the end user. This is because the type of application determines whether or not a sink is created in the first place.

The remuneration of sink services in exchange for certificates requires systems that are subject to rigorous and fully documented accounting principles, that effectively counteract potential double counting, and that are forgery-proof and consistently auditable. Systems that meet these requirements are also suited to being linked to tax and disclosure systems. They can in addition be used to create financing and trading systems to cover the financing requirements for the creation of sinks.

Although it appears obvious in principle to create links to national and international emissions trading systems, it is not appropriate to offset sinks and emissions against each other. On the one hand, the extent and speed with which sinks have to be created depends on the success of emission reduction, but on the other hand, in all realistic scenarios, sinks need to be created to a considerable extent. Moreover, the prices for which high-quality and rigorously accounted permanent sinks can currently be created are far higher than the current prices for emission certificates. From an economic point of view, this suggests on the one hand, tightening national and international requirements for emission reductions and thus raising prices and, on the other hand, keeping the pricing, remuneration and, where appropriate, trading in certificates for sink services separate. A look at the emissions and sinks budgets resulting from 1.5° scenarios (as shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**) shows that in a few decades it will be necessary to create carbon sinks that far exceed emissions. Net zero will no longer be good enough after 2050, when the task will be to reduce excessive CO_2 levels to a level compatible with climate objectives by means of active carbon removal. Even then, the respective mandatory and voluntary targets and markets will have to be separated in a sensible way, while taking into account their interdependence.

Of course, CO_2 certificates based on the sink technologies as mentioned here already exist, especially in the voluntary market. However, the EBC guidelines for carbon sinks (EBC, 2020) are the first standard on the basis of which carbon sink certificates can be created in accordance with the accounting principles outlined here. Accordingly, there are currently hardly any markets for carbon sink certificates in this sense. These novel and initially voluntary markets play a pioneering role, both because they enable companies, public institutions and private individuals to implement an appropriate, science-based climate strategy that includes the creation of carbon sinks, and also because they can show which instruments are effective and efficient. Functioning systems, initially on a voluntary basis, can gradually be transferred or integrated into state-regulated systems.

In order to obtain an indication of the prices of sink certificates, it is necessary to be able to compare the storage capacity of the sinks. The comparison of the sequestration curves in the following graph shows exemples of sink performances of different carbon sinks over a period of 100 years. The respective end points correspond to the expiry dates specified in typical projects (contractually). Of course, the expiration of this period does not necessarily mean the destruction of the sink (for example, through clearing).

However, at this point the contractual partners are free to change management practices, harvest timber or otherwise claim the sink benefit.

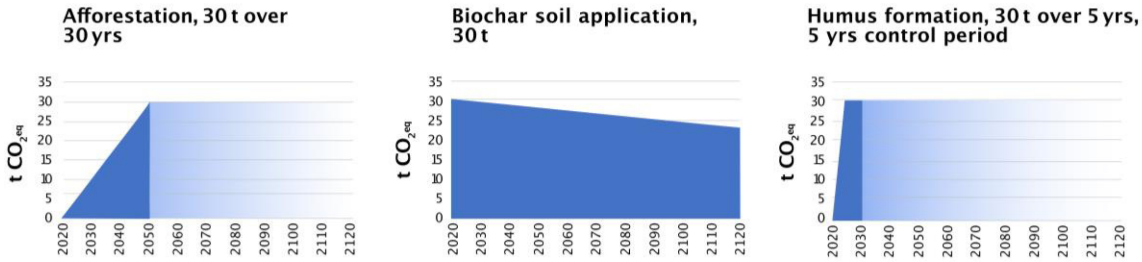

Figure 8: Comparison of the sequestration curves of different carbon sinks. In all cases it was assumed that a maximum of 30 t CO_2 equivalents are bound.

Quantification of the climate benefit of different types of carbon sinks

A simplifyied, but initially suitable standardization for the service provided is the unit tonnes CO_2 equivalent multiplied by the number of years (in short "ton years"). For this, it is necessary to define an appropriate time horizon – otherwise permanent sinks such as the use of biochar in concrete, for example, would not be comparable with forest projects. A time horizon of 100 years seems appropriate, because this is long enough to avoid unwanted speculation, it is consistent with the horizon of the end of the 21st century, which is usually used in climate policy and climate science, and it is easy to communicate.

Let's consider a simplified example of a reforestation project on a defined area that runs for 30 years (example of common practice) and ideally binds exactly one tonne of CO_2 per year, i.e. has bound 10 tonnes in year 10 of the duration. Within the project duration, the project will therefore yield: ½ x 30 years x 30 tonnes = 450 tonne years (area of the triangle: one half x base side x height). In comparison, the illustrated sink on the basis of biochar depicted in the figure above, assuming an annual degradation rate of 0.3% over 100 years, produces a sink capacity of approximately 2,600 tonne years (area below the curve).

In the voluntary market, about 35 € per tonne of CO_2 equivalent added is currently paid for high-quality reforestation projects. This means that a tonne year for such a project costs an average of € 2.33. Well-known compensation schemes for humus build-up tend to have an even shorter contract period and are therefore more expensive per contractually guaranteed tonne year. Sink certificates based on biochar applications are currently offered on the voluntary market for 100 € per tonne of CO_2 equivalent over 100 years, i.e. 1 € per tonne year. Even if the price of 100 € for the certificates seems high at first, it is comparatively cheap in view of the service provided. These prices for sinks based on carbon-preserving applications of biochar allow the price of biochar products to be reduced by 10 - 20%, making them economically viable for a wider range of applications.

With a view to the assessment of the consequential damage to the climate by the German Federal Environment Agency, which estimates the consequential costs of emissions to be at least 180 € per tonne of CO_2, higher prices appear appropriate in the long term (Federal Environment Agency, 2/2019).

5 Recommendations for action

Treat climate change as a crisis, tackle climate neutrality now: Climate change is a real and serious threat and must be treated as a fundamental crisis. The problem cannot simply be sat out and there is no looking away. It must be the task of politicians, but also of each individual, to reduce CO_2 emissions, as well as other greenhouse gas emissions within their respective sphere of influence, steadily and emphatically. As renewable energies continue their impressive advance, attention is turning to the importance of reducing greenhouse gas emissions from agriculture (CO_2, methane and nitrous oxide) and this issue urgently needs to be more strongly addressed.

Acknowledge the necessity of sinks and take the first steps now: Anyone in politics who does not take the necessity of building carbon sinks seriously implicitly accepts a man-made global temperature increase of 3 - 4 °C and thus a social and ecological upheaval of barely imaginable dimensions. Therefore we call upon policymakers:

- **to set up research programmes** to clarify open questions and to develop technology for solutions which create carbon sinks. Important issues in this context are ensuring environmental compatibility, improving the understanding of cause-effect relationships and reducing costs.
- **initiate market introduction programmes** for carbon sinks. Solutions that are already proven, do not involve relevant risks and are already scalable must be rolled out now.
- **Set** rapidly increasing **target volumes for the creation of carbon sinks**, comparable to emission reduction targets.
- Consistently **separate** the **carbon balance for emissions** from **carbon sinks**. If targets for emissions reduction and for the creation of sinks are not kept separate, there is a danger that sinks will be used to compensate for deficits in emissions reduction. Moreover, sinks would probably not be built up quickly enough due to their current higher costs compared to emission reductions.

Use biomass pyrolysis and biochar as one component of the solution. With regard to biochar as a carbon sink and against the background of the factual arguments presented in this paper, we call on policymakers and governments to do the following:

- **Recognize biomass pyrolysis** as a **key technology in the fight against climate change** and as an aid to increasing resilience.
- **Help** the production and use of biochar **to make a breakthrough on a broad basis.**
- Wherever questions arise, **base** the **dialogue on the latest scientific findings**.
- Help **standards and certifications to be recognized and applied** and be **further developed**. This applies both to biochar and to the accounting of carbon sinks.

- **Rethink** the **approach to biomass**: The material use of wood/biomass must be given the highest priority. Any combustion of biomass is a missed chance to create a carbon sink. Wherever it is reasonably possible pyrolysis must be preferred to combustion

Seize opportunities for jobs and technological leadership: There are numerous innovative mechanical engineering and technology companies in Europe that have not only reduced process emissions in the manufacture of biochar to a completely harmless level but also secured pollutant-free pyrolysis products, making them world leaders.

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