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Biochar in the View of Climate Change Mitigation: the FOREBIOM Experience

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Abstract

Biochar is currently one of the dominant topics in soil research, despite the fact that it is not a new discovery. It has the potential to address some of the most pressing questions humanity is currently facing, that is climate change, food security, energy security and environmental pollution. However, a soil system is very complex and together with the multitude of biochar production settings and nearly infinite number of potential feedstock resources it becomes evident that there is no single solution for these challenges available. This is specifically an issue when addressing the potential of biochar for climate change mitigation via reduction of greenhouse gases (GHG). Systems approaches are needed, covering the entire supply chain and backed up with life cycle assessments to ensure a positive impact by using biochar as a tool for environmental management.

This chapter provides a summary and brief introduction of the subsequent chapters of this book, with a focus on biochar for climate change mitigation, including an economic assessment of GHG abatement costs. The FOREBIOM project will be briefly introduced and results on biochar erosion after amendment of a forest floor are presented.

1.1 Introduction

Biochar, 'a solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment' (IBI, 2013), has become one of the dominant research topics within the scientific soil community during the past years. Scientific conferences and meetings focusing on soil issues feature a considerable number of biochar related contributions. Unlike the case in a number of hypes in science, the biochar topic seems to be attractive also to the public, at least in some countries. The results of a simple web search on biochar application are just overwhelming, starting from private small-scale initiatives all the way through to industrial-scale production. One can easily retrieve reports, photos and even videos on

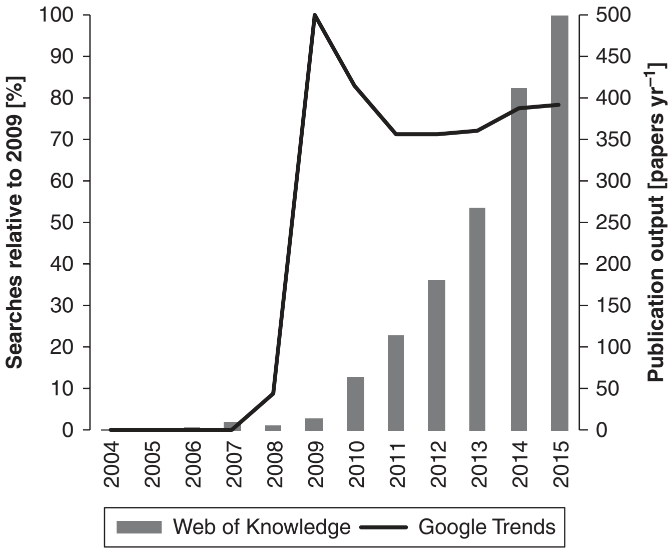

Figure 1.1. A comparison between scientific and public interest in biochar since the beginning of the recent boom at around 2006. Grey bars show the scientific output of literature (scientific articles and reviews with the term "biochar" in the title) according to the Institute for Scientific Information (ISI) Web of Knowledge (now Web of Science). The solid black line represents the relative share of searches based on the year 2009, where most searches occurred.

YouTube, explaining how to build your own biochar reactor and how to use biochar in your home vegetable garden. Biochar science is currently in a phase of rapid growth and the annual publication output is still increasing since beginning in around 2006. It is interesting to note, however, that the public interest in biochar, expressed as the number of web searches on Google, seems to have already peaked in 2009 and remains on a relative constant high level since then (Figure 1.1). It is assumed that Google Trends represents public interest in biochar, although a share of the searches likely also originates from experts. However, we hypothesize that they would use more complex search terms or combine biochar with other attributes. A closer analysis in terms of regional interests reveals that until January 2016, the leading country in terms of search volume was Australia, followed by Canada, the United States and the United Kingdom. India is the leading developing country, with 24% of the search volume, which is comparable to the figures in Germany or Italy. The reason for the rapid growth in popularity might be that it has been claimed that using biochar as a soil amendment may be helpful in addressing some of the global key challenges, such as population growth and increasing demands for food and feed supplies, climate change, and a recent boom in renewable energy. Indeed, the potentials seem enormous, but it is also clear that biochar alone is not the key for all these issues. A very comprehensive introduction and presentation of current knowledge of biochar is offered in the recently published second edition of *Biochar for Environmental Management: Science, Technology and Implementation* (Lehmann and Joseph, 2015a).

Biochar represents the solid residual when heating biomass to above 250°C in an oxygen-free or -depleted atmosphere, with the specific aim to use it as a soil amendment or growth medium. The production process is generally called pyrolysis and is explained in detail later in this book (Chapters 10 and 12). During pyrolysis, volatiles and water are driven off and carbon is re-organized in fused aromatic ring structures that are more recalcitrant to decomposition as compared to the carbon compounds of the original biomass. As the pyrolysis temperature (highest heating temperature, HHT) is increased, a large number of micro-cracks are formed, increasing the surface area and thus the potential chemical reactivity. Although the chemical characteristics change is remarkable, including a relative enrichment in carbon (C), calcium (Ca), phosphorus (P), and potassium (K) among others and typically a depletion of hydrogen (H) and oxygen (O), as well as the reorganization of C, there are only minor morphological impacts on the visible macro-scale, despite the black colour.

The material itself can be found in many forms in a large number of ecosystems worldwide, resulting from wildfires, where it is called char, or purposely made in kilns, where it is called charcoal. Charcoal is traditionally used as carrier of thermal energy. The use of both char and charcoal has a long history and is closely related to the development of human culture. The Chauvert cave in Southern France presents some of the oldest char drawings with an age of around 30,000 years BP (before present) according to radiocarbon dating (Pettitt, 2008). Much later in history, it was the most important source of thermal energy for smelting ores in developing cultures, until its peak use when it fuelled the industrial revolution from about the middle of the eighteenth century until fossil resources finally replaced charcoal. Woodlands, especially in relatively close proximity to urban areas, still show features such as abandoned forest railways, even plateaus in rugged terrain or simply distinct field names that indicate the significance of charcoal production in past times. Charcoal has clear advantages over fuelwood, especially in urban areas where the consumption of energy is high. As volatile matter and water is removed during the pyrolysis process, its weight is reduced and therefore transportation is easier and the emissions are lower during combustion, making it even suitable for indoor use if air circulation is ensured. Therefore, it is still of major importance in a number of regions worldwide, especially in Africa, South America and Southeast Asia, where charcoal is still produced using traditional methods (Chapter 13). However, as biochar is made for a specific purpose other than burning and harvesting thermal energy, it may be produced from different biogenic feedstock materials. Consequently, not all kinds of biochar are suitable for combustion and it might overlap with charcoal only under certain conditions (feedstock material and production characteristics etc.).

This diversity of biochar offers a great opportunity for producing materials that deliver dedicated environmental functions based on the properties of the soils on site scale and the desired environmental response after biochar amendment. Specific biochar properties may be achieved by the selection of feedstock resources or a blend of different materials, the pyrolysis conditions (especially HHT), mixing of different types of biochar, or post treatment, such as composting of biochar with other organic materials. There are a number of different terms in the literature for this targeted biochar production, such as 'designer biochar', 'bespoke biochar' and 'fit for purpose biochar', among others. Bespoke biochar may fulfil a specific and predictable function in a complex environment that includes various biotic and abiotic factors on a number of spatial scales. The basis of a targeted use is therefore a sound understanding of the site conditions, as well as the processes and mechanisms involved, especially in relation to soil microbiology and soil chemistry. In addition, it is necessary to formulate standards and guidelines to facilitate and promote biochar production and use in a safe and efficient way. The International Biochar Initiative (IBI) as well as the European Biochar Research Network (EBRN), among other institutions, developed biochar standards and certificates, with the aim of setting industry standards that ensure a certain level of quality and safety. In particular, heavy metals, which are part of the initial biomass in low doses, might be accumulated in the biochar after pyrolysis and therefore pose environmental risks. The secondary formation of potential hazardous contaminants is controlled by the feedstock material and the pyrolysis conditions. There are a range of potentially harmful contaminants that can be formed during pyrolysis, such as polycyclic aromatic hydrocarbons (PAHs) or dioxins.

A more direct and immediate use of biochar can be achieved by reducing the complexity of a biochar system. On local scales, and for distinct spatially confined scales, there are a number of possibilities to utilize biochar. This is especially the case in urban areas and in combination with new approaches of modern architecture. A worldwide trend of urbanization and a consequent city compaction threatens urban green space and, hence, a sustainable urban development with careful planning and new approaches is needed (Haaland and van den Bosch, 2015). The advantage of the low weight of biochar, in combination with a large surface area, makes it an ideal component for biochar-soil mixtures used on roofs or other elements of a building. One such example can be found in the 1 Utama shopping centre in Kuala Lumpur, the capital of Malaysia (Chapter 8). It is one of the largest shopping centres worldwide and features a rain forest as well as a rooftop garden, which are both well integrated in the building structure (Figure 1.2). Biochar plays an essential role as a growth medium in this particular example.

In fact, research already steps beyond green space when considering tight material cycles to reduce the environmental footprint. Such material cycles can even equal the boundaries of a single building, which makes them to a certain degree autonomous. For instance, biochar can be used for sustainable sanitation (Schuetze and Santiago-Fandiño, 2014). Likewise, Chapter 5 demonstrates the use of biochar in a system with clearly defined boundaries, where it also plays a role in sanitation to recover essential nutrients, such as nitrogen, phosphate and potassium, in the Berlin-Dahlem Botanical Garden.

1.2 Summary of the Contents of This Book

The initial idea of the underlying FOREBIOM project (potentials for realizing negative carbon emissions using forest biomass and subsequent biochar recycling) was to foster collaboration among South Korea and European countries towards the potentials of biochar for climate change mitigation. The scope of the current book is widened to

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Figure 1.2. The "Rain forest" (a) and the "Secret garden" (b) in the 1 Utama shopping centre in Kuala Lumpur both use a mixture of biochar, coconut fibre and clayey subsoil as a growth medium. The ratio of the three compartments was adjusted according to the actual vegetation. Charcoal briquettes from sawdust, produced for barbecue purposes, were used to provide biochar. Photographs by V.J. Bruckman. (A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)

ensure a holistic approach and a broader geographical perspective is included. A focus of this book is biochar production and use from a forestry perspective, as forests represent a potentially large source of biomass, and biochar application in forests may be of interest in certain circumstances (Chapters 4 and 15). The book consists of four major sections, divided into a more cross-disciplinary section, and three key steps involved in the biochar supply chain, each representing a section of four to five chapters (Figure 1.3). The key steps were identified and discussed during the FOREBIOM workshops and it was agreed that these should be considered in a comprehensive assessment of biochar potentials. Consequently, we introduce each step separately (1.2.1–1.2.3) and present links to the relevant chapters. On the other hand, we refer to the cross-disciplinary chapters (2–5) throughout this introductory chapter. The examples of integrating biochar as a functional element in Berlin and Kuala Lumpur demonstrate that the potential uses are indeed vast. Despite the fact that practical use of biochar does not play a major role at this time for a number of reasons, it requires a holistic and systems approach to ensure that biochar can be part of a sustainable

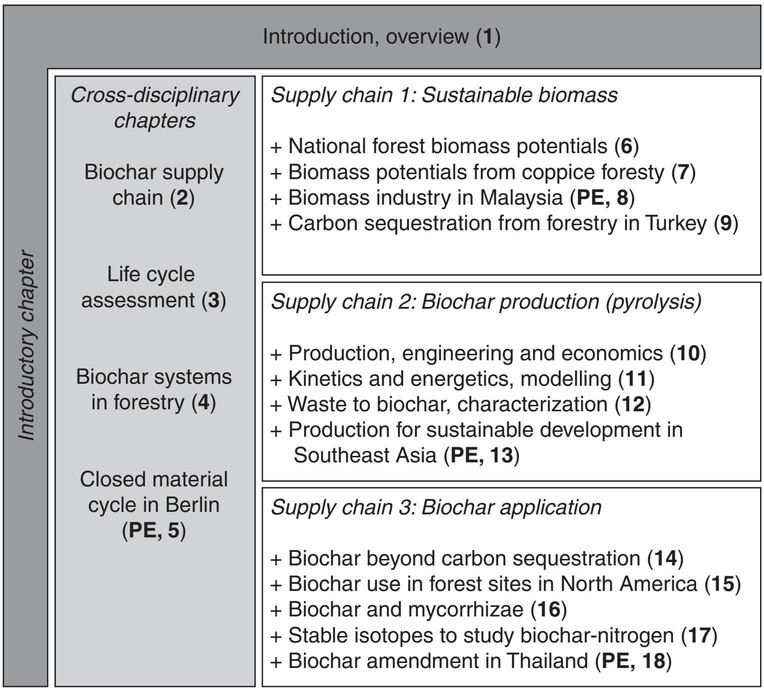

Figure 1.3. Summary of the contents of this book, divided into the introductory chapter and four major sections. The chapters are categorized according to their main focus and their numbers are given in brackets. Chapters describing practical examples (PE) or case studies are indicated. The three main elements of the supply chain are described in detail in Sections 1.2.1–1.2.3.

development. Suitable tools in order to account for the net carbon impact of a biochar system, such as the life cycle analysis (LCA), can provide essential information on the sustainability in terms of C balance (Chapter 3).

1.2.1 Sustainable Biomass

The production of biochar requires biomass. The choice of the appropriate biomass feedstock may be determined by the desired properties of the final product, biochar, but often a more practical constraint dictates the type of biomass used. The availability of inexpensive biomass is currently (and probably will always be) the main factor influencing the potential of biochar production and to some extent the properties of the final product. This makes all kinds of waste biomass ideal candidates as feedstock for pyrolysis. This approach can also help to close material cycles and reduce the GHG footprint by replacing external purchases of fertilizers and growth media (Chapter 5). Biochar derived from woody plant biomass has the advantage of an inherent porous structure and a high C content, while the potential availability in many regions is high. However, biomass from forestry and agriculture, which together represent the most important potential source of plant biomass for pyrolysis, is demanded by a whole range of industries. This became specifically an issue in recent years, when the term ‘bioeconomy’ was coined and new technologies were developed to use biomass as a source for energy or other industrial feedstocks. Indeed the consumption of biomass is increasing and there is a need to clearly define sustainable potentials of biomass to support a meaningful green economy. One such approach can be based on an integrated assessment, where a theoretical potential is firstly calculated and then further decreased by a subset of constraints, considering for instance accessibility, environmental services, market price, nutrient balance and land tenure (Chapter 6). Even if this approach provides rough numbers for the entire forestry sector, it is also possible to determine potential waste streams (i.e. from sawmills or the wood processing industry) that represent potentials for biochar production. We show that some of these are traditionally used for charcoal production in Southeast Asia (Chapter 13). It was demonstrated that policy regulations can have a strong impact on the GHG balance of the forestry sector. Forests in Turkey represent a net sink of C and reforestation activities ensure that this trend remains unchanged. Currently there are no considerable incentives to increase biomass yields, although there is a gap between supply and demand. Consequently, agricultural biomass is being used extensively and there is strong competition in the biomass market (Chapter 9), making the production of biochar a challenge. At the same time, forests sequester large amounts of C, which can be a promising alternative strategy, compared to biochar.

Traditional forestry usually aims at the production of high-quality timber and the potential biomass waste is limited and also demanded by other industries (i.e. woodchip or pellet production). Biomass plantations can therefore produce biomass that is dedicated for use in energy or raw material production at much higher efficiencies when using fast-growing species in combination with short rotations. Such systems demand high standards of the soils, and fertilization is commonly necessary to compensate for the high nutrient losses. Biochar can be a potential tool to help to sustain the soil functions in such biomass plantations or to help remediate problematic sites (Chapter 4) while enhancing the efficiency of fertilizer use and the minimisation of GHG emissions such as nitrous oxide (N_2O) (Chapter 14). Short-rotation forestry was once a major source of biomass for energy and other products that require small stem diameters. Unlike the case in plantations, forests consisting of endemic species were coppiced, after which woodlands regenerate from resprouting from stumps or root suckers (Bruckman et al., 2011). This specific type of silviculture is seen as a potential source of biomass as it is sustainable and may even help to increase biodiversity (Chapter 7).

Woody biomass can also be provided in large quantities from the agriculture sector. In Malaysia, for instance, huge areas are cultivated with oil palms and rubber trees. Both crops provide large amounts of lignocellulosic biomass, suitable for a range of applications, including pyrolysis (Chapter 8). Innovative examples of biochar utilization may stimulate further research and development and prove that a successful application is possible under certain circumstances, as demonstrated in the 1 Utama shopping centre (Figure 1.2).

1.2.2 Biochar Production (Pyrolysis)

Virtually any organic material with a substantial amount of C can be used for producing biochar. The process of pyrolysis can be described as a method of thermal decomposition, as complex chemical structures are decomposed into a number of chemical compounds that differ significantly from each other. Moreover, the resulting products can be a mix of solid, liquid or gas and the ratio of these products is largely dependent on the pyrolysis conditions, especially the HHT and process duration. The pyrolysis conditions, together with the feedstock type, have a strong impact on the properties of biochar (Zhao et al., 2013; Kloss et al., 2012). C retention and biochar recalcitrance are two of the important properties with regard to immediate C sequestration, which can be greatly influenced by the process settings. In fact, a range of different pyrolysis reactors were developed, where biochar represents either the main product or in some cases a byproduct of an industrial process (Chapter 10). The products that can be derived from pyrolysis range from solid (e.g. charcoal, activated carbon, carbon fibres, ash, soot, fertilizers) to liquid (e.g. bio-oil, pyroligneous acid (Chapter 13), functional chemicals) to gaseous compounds (e.g. methane, ethane, propane, hydrogen) and all represent valuable bio-products (Chapter 12). Some of these products may be used directly (e.g. biochar for soil amendment), as a feedstock for further industrial processes or can be converted into energy. While the utilization of the gaseous products represents standard technology that is already available on the market, it is somewhat problematic with the liquid product of bio-oil. Its chemical composition is very complex, with a high water content, and it is corrosive. Hence, it needs a range of purifying steps to be ready for use in a variety of stationary energy applications (Chapter 10).

The production of biochar is not a new technology, as there is a long history in producing charcoal. Traditional methods are still widely used despite the low efficiency, uncertain process conditions and therefore varying qualities and high emissions of potentially hazardous components during pyrolysis. However, recent developments aim at improving these technologies and making them a viable source of income for local communities (Chapter 13). Although the main commodity will remain charcoal as there is a high domestic and international demand, residues from charcoal production may be used as biochar after comprehensive analysis and characterization of this material to avoid any negative consequences as a result of contamination. The practical questions for potential operators of pyrolysis reactors are whether there is a market that can sustain biochar production and whether a valorization of byproducts is possible. A careful economic assessment is important and it has to include feedstock costs, the development of biochar reactors, potential subsidies and additional revenues from bio-energy co-production, and a potential impact from carbon trading schemes and markets (Chapter 10). The combined production of bioenergy and biochar offers an interesting approach in terms of climate change mitigation, as a certain share of the original carbon in biomass is used to substitute fossil fuels and the residual solid biochar may contribute to a long-term C pool in soils, where it ideally improves soil properties. This can lead to a secondary effect through increased biomass productivity as a consequence of higher fertility. Modern pyrolysis reactors can produce

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biochar continuously and the process is self-sustaining once the pyrolysis process is started (Lehmann and Joseph, 2015b). The ratio between harvestable energy and other products can be predicted using specific kinetic models that describe the thermal decomposition of a biomass feedstock by explaining the chemical reaction rates in relation to the process conditions (Chapter 11). Such approaches are of major importance as reactors can be described by a set of mathematical equations, and hence provide a basis for the design and virtual testing of new pyrolysis approaches that include the production of biochar as well as other products, such as bio-energy, simultaneously. Different scenarios can be computed and optimal settings defined before a potential plant is built, which reduces the costs and efforts for system testing and evaluation.

1.2.3 Biochar Application as a Soil Amendment

In the final step of the supply chain, biochar is being incorporated into the soil, mixed with soil and/or other compartments for creating growth media or distributed on the soil surface. The soil system is very complex, with numerous interactions, and the introduction of biochar as a soil amendment may trigger certain responses that impact both soil physics and soil chemistry. Without any consideration of biochar and soil properties, the effect may be also negative, even in terms of C sequestration. Therefore, a sound understanding of the processes and mechanisms involved is of key relevance and there is no standard solution for how to amend a soil with biochar to achieve the desired response in the most efficient way. However, the current trend in biochar research is based on a range of expectations for biochar as a tool for environmental management. Key functions that biochar can provide are the improvement of nutrient availability and water retention, reduction of GHG emissions (Chapter 14), sorption of pollutants and growth-inhibiting substances such as heavy metals and salts, storage of recalcitrant C in the soil profile, improvement of soil physical properties and providing a suitable habitat for soil biota (Chapter 16). The efficient and targeted provision of one or more of these desired functions does not only depend on the feedstock and pyrolysis conditions, but to a large extent on the actual soil properties, the climate conditions, the type of vegetation and the resulting quality and quantity of existing soil organic matter (SOM). The above mentioned functions addressing GHG are to a great extent coupled with the nitrogen (N) cycle. Biochar may significantly influence soil N cycles and processes by altering nitrification, adsorption of ammonia, which has shown to be bioavailable (Taghizadeh-Toosi et al., 2011), and by increasing the storage capacity of ammonium, resulting in effects on plant nutrition, GHG emission from soils, and leaching of nitrate (Clough and Condron, 2010). Especially in temperate regions, reducing GHG emissions by using biochar to influence the N cycle turns out to be a promising strategy in reducing N_2O emissions (Hüppi et al., 2015) (Chapter 14). N_2O outcompetes CO_2 by a factor of 265 in terms of radiative forcing over a period of 100 years (Myhre et al., 2013) and is hence a very effective GHG. There has been significant progress in recent years in assessing the mechanisms and processes behind biochar–nitrogen relations.

Studying stable isotopes has been shown to be a viable method with a number of recent discoveries, and it currently represents a highly dynamic research field (Chapter 17).

Soil fertility is to a large extent determined by the activity and abundance of soil biota, and it was shown that biochar can have a strong impact on it (Thies et al., 2015). High activity in soil microbial communities implies higher nutrient mineralization rates and therefore higher potential biomass productivity, but on the other hand it could lead to elevated soil GHG emissions. Many productive species in agriculture and forestry depend on symbiotic mycorrhizae, helping to extend the accessibility of mineral nutrient and water pools that are otherwise inaccessible for fine roots. Biochar can provide a suitable habitat for mycorrhizae and it is suggested that a combination of biochar amendment and inoculation of specific mycorrhizae shows the highest increase in biomass productivity (Chapter 16). This is of special concern in areas suffering from drought and it may be a successful strategy to reduce the amounts of fertilizer used via increasing the efficiency of their uptake. This would be a positive impact on the C budget as the production of mineral fertilizer requires large amounts of energy and the rates of GHG emissions and leaching may be lower. Small-scale local solutions of biochar production and subsequent soil amendment can contribute to food security and reduced pressure on forest land, especially in tropical and subtropical climates where biochar can significantly improve soil properties (Chapter 18). Such local biochar systems must be evaluated and tested from the point of view of sustainability, as promising examples may have a strong demonstrating function for regional development.

Biochar amendment is usually demonstrated in agricultural systems, and studies within forest ecosystems are rare. Therefore, we were explicitly looking at potential pathways to utilize biochar in forest ecosystems, which makes sense where a closed material cycle is anticipated or in a circular biochar system (Chapter 4). One of the key challenges in forest ecosystems is that it is in most instances, especially in traditional forestry, impossible to integrate biochar into the soil horizon and, hence, it needs to be spread on the surface (Bruckman et al., 2015b). This implies temporal dynamics in the effects of biochar amendment; immediate effects are likely to influence plant nutrition, while further effects are subject to integration of biochar in the organic and subsequently mineral soil horizon (Sackett et al., 2015). The pyrolysis of harvesting residuals, with subsequent amendment of the resulting biochar, may help in restoring degraded forest sites with a high impact from logging. Key areas of targeted biochar use can be skid trails or log landings, while utilizing fuelwood that otherwise poses a risk in regions threatened by wildfires (Chapter 15). Leaching of nutrients at the time of harvesting may be reduced, and therefore biochar can play an important role in protecting water quality in rivers and streams and help to minimize losses of mineral nutrients from the system.

1.3 Biochar and GHG Mitigation

The negotiations at the 2015 Paris Climate Conference (COP21) were undoubtedly a necessary step forward to a legally binding, multinational universal agreement on climate with the aim to counteract climate change. As anthropogenic GHG emissions