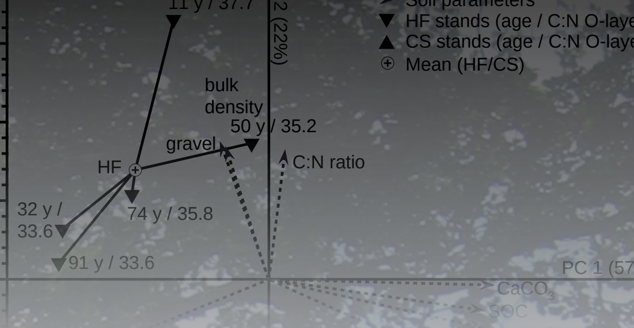

Carbon in *Quercus* forest ecosystems

Management and environmental considerations

ÖAW
Austrian Academy of Sciences

BOKU

Dissertation

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Dissertation
presented for the fulfilment of the requirements for the degree *Dr. nat. techn.*
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Submitted by
Dipl.-Ing. Viktor Johannes Bruckman, Bsc.

Vienna, September 2012

Lovingly dedicated to my son Arnold Jian-An
and my wife Yen-Sun

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In-situ observations require reliable partners and I must admit that we were in a lucky position to have found them. Without the allowance to set up our investigation plots and sample soil as well as aboveground biomass (including felling of trees), we would not have been able to conduct our research. Therefore, I would like to thank the Forst- und Gutsverwaltung Schönborn KEG and Forstbetrieb Benedikt Abensperg und Traun for their great support and hope that our findings are valuable for them.

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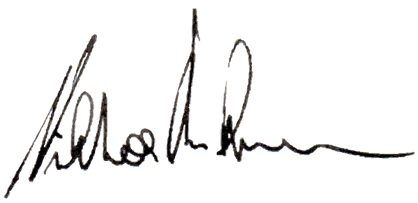
Our son, Arnold Jian-An makes every day a good day. He is able to make me smile no matter what challenges or difficulties I am facing. Thank God for this wonderful family.



THANK YOU

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Abstract

Carbon (C) is an essential element for all forms of life we know and its reduced or not fully oxidized forms are the major source of energy used by humans. At the same time it is at centre stage in context of climate change and subsequent negative consequences for humanity. Forests represent the largest pool of terrestrial C, directly situated at the reactive soil-atmosphere interface and their management has the potential to significantly influence atmospheric C concentrations. The aim was to highlight the importance of forests in the global C cycle and to study C pool dynamics along a stand development in view of C management. The present work consists of three parts:

Part 1 presents a holistic overview on current knowledge of anthropogenic C metabolism and the resulting climate change. The role of forests in sequestering C is emphasised in context of forest management and biomass production for energetic utilization. Promising examples of different strategies to maximize C sequestration are presented and discussed.

Part 2 comprises a paper on dynamics of organic C pools along a rotation period in two *Quercus*-dominated chronosequences in a high forest and coppice management system. The results suggest that soil organic carbon (SOC) pools are relatively low in both systems and the impact of logging on SOC is low. Fine root dynamics differ remarkably between the two silvicultural management systems. The chronosequence approach was suitable to describe aboveground biomass C pools but it turned out that it is an inappropriate method to study SOC dynamics in the proposed study setup.

Part 3 proposes an improved method to assess soil inorganic carbon (SIC) on the same plots. The current, gas-volumetric Scheibler method has a number of disadvantages. Hence a new approach of combining Fourier Transform Mid-Infrared Spectroscopy (FT-MIR) and X-ray diffraction (XRD) and subsequent partial least squares regression (PLSR) modelling is presented. The model shows a good performance in predicting carbonate contents across the study region. A combination of the two methods FT-MIR and XRD has the potential to improve accuracy of SIC determination.

Keywords: Climate change, Biomass, Carbon, *Quercus petraea*, Chronosequence, Carbonate

Zusammenfassung

Kohlenstoff (C) ist ein essenzielles Element für alle uns bekannten Lebensformen und ist in reduzierter oder nicht vollständig oxidierter Form die wichtigste Energiequelle für den Menschen. Zur selben Zeit steht er im Kontext des Klimawandels und der daraus folgenden negativen Konsequenzen für die Menschheit im Mittelpunkt der Klimadebatten. Wälder repräsentieren den größten terrestrischen C Vorrat welcher zudem direkt an der reaktiven Schnittstelle zwischen Boden und Atmosphäre angesiedelt ist. Daher hat Waldbewirtschaftung das Potential die atmosphärische C Konzentration signifikant zu beeinflussen. Das Ziel der Arbeit ist die Hervorhebung der Rolle des Waldes im weltweiten C Kreislauf und das Studium der dynamischen C Vorräte während der Bestandesentwicklung in Hinblick auf C Management. Die vorliegende Arbeit besteht aus drei Teilen:

Teil 1 bietet eine ganzheitliche Übersicht über aktuelles Wissen des anthropogenen C Metabolismus und den daraus resultierenden Klimawandel. Die Rolle der Wälder als C-Senke wird im Kontext der Waldbewirtschaftung allgemein und der Biomasseproduktion für energetische Verwertung im Speziellen besonders hervorgehoben. Vielversprechende Beispiele verschiedener Strategien zur Maximierung der C Sequestrierung werden vorgestellt und diskutiert.

Teil 2 umfasst eine wissenschaftliche Arbeit über dynamische C Vorräte entlang einer Rotationsperiode in zwei eichendominierten Chronosequenzen im Hochwald- und Ausschlagwaldsystem. Die Ergebnisse deuten darauf hin, dass die organischen Bodenkohlenstoff (SOC) Vorräte in beiden Systemen relativ gering sind und dass der Einfluss der Ernteentnahmen auf die SOC Vorräte gering sind. Die Feinwurzeldynamik unterscheidet sich wesentlich zwischen den beiden waldbaulichen Systemen. Der Chronosequenzansatz ist sehr gut geeignet um oberirdische C Vorräte zu beschreiben, erwies sich aber als ungeeignet um SOC in dem verwendeten Studiendesign zu untersuchen.

In Teil 3 wird eine verbesserte Methode zur Erfassung des anorganischen Bodenkohlenstoffes (SIC) vorgeschlagen. Die aktuell weit verbreitete, gasvolumetrische Scheibler Methode ist mit einer Anzahl an Nachteilen behaftet. Daher wird ein neuer Ansatz einer Kombination der Fourier-transformierten Spektroskopie unter Verwendung des mittleren Infrarotbereiches (FT-MIR) und der Röntgendiffraktometrie (XRD) mit anschließender Regression der partiellen kleinsten Quadrate (PLSR) Modellierung präsentiert. Das Modell zeigt eine zufriedenstellende Leistung in der Vorhersage der Karbonatgehalte innerhalb der Studienregion. Eine Kombination der beiden Methoden FT-MIR und XRD hat das Potential die Genauigkeit der SIC Quantifizierung zu verbessern.

Schlüsselworte: Klimawandel, Biomasse, Kohlenstoff, Traubeneiche, Chronosequenz, Karbonat

Carbon in *Quercus* forest ecosystems
Management and environmental considerations

Overview

Life on our planet is impossible without carbon (C). It is an essential element for all forms of life we know because it is relatively abundant and it can form a large range of bounds with other elements. In its reduced or not fully oxidized forms, C represents the major source of energy used by humans but at the same time it is at centre stage in the context of climate change and its negative consequences for humanity. Forests represent the largest pool of terrestrial C, situated directly at the reactive soil-atmosphere interface. Managing forests and its soils is consequently controlling fluxes between these two pools.

The first chapter aims at providing an overview on C metabolism and the increasing anthropogenic influences and subsequent consequences. It summarizes current knowledge on rising atmospheric CO_2 concentration and the implications for climate. Mechanisms for mitigating climate change and alternative low-C emitting sources of energy are discussed. A broad context is intentionally presented as it reflects the field of interests and interdisciplinary activities of the author during the past years.

The successive chapter focuses on the role of forests in C sequestration with special emphasis on soil processes and the importance of nitrogen (N) in controlling C pools and fluxes. Regulatory mechanisms for sustainable production and sequestration are deliberated.

The next chapter presents aspects of biomass production for energetic utilization with focus on C turnover. The Japanese Satoyama coppice management is introduced as an integrative management system capable of providing multiple ecosystem services in densely populated areas. Among others, the potentials of biochar in sequestering carbon while enhancing soil properties are discussed. This topic is selected based on a project initiated by the author. It was recently selected for funding.

Finally, the relevance of the two scientific papers which are submitted as doctoral dissertation and their scientific and practical impact is discussed and the actual manuscripts are presented. Abstracts of various conference contributions (lectures and posters) in context of the dissertation project are attached as a "work-in-progress" documentation.

Background

The Earth's age is estimated to be 4.5×10^9 years. During this vast amount of time, continents have formed, soils developed, providing the basis for terrestrial vegetation with higher plants. Evolution of biodiversity began and species have been wiped out as a consequence of massive volcanic eruptions and impacts of extra-terrestrial objects. However, within a comparably very short period of only 0.2×10^6 years, the human race evolved in Africa (McHenry, 2009) and spread all over the planet. The Holocene, starting from about 11.5×10^3 years ago is the last interglacial time period, providing relatively stable climatic conditions supporting human development. The Holocene is by far the shortest epoch in the geological time scale and many surface bodies we live on (e.g. soils, river deposits, and deltas) formed during that epoch (Zalasiewicz et al., 2011). Epochs are characterized by distinct rock sediments that were deposited during particular time intervals. Certainly urbanization, as a clearly visible indicator of expanding populations, will one day lead to very interesting sediment layers and future generations of (alien?) geologists and archaeologists, who will be astonished at the complexity of sediments full of surprises. We are considerably influencing the earth's biosphere in regularly decelerating and accelerating natural processes, destruction and creation of ecosystems and even altering global temperatures with a multitude of consequences (most of which are currently not well understood). The main driver behind this development is population growth in combination with changing lifestyles. Massive amounts of finite resources and energy are used. The starting point of this development lies not far behind the beginning of the industrial revolution, although a number of anthropogenic activities (e.g. deforestation for agriculture, drainage of peat lands) had a marked impact on the environment well before the industrial revolution. However, the manipulation of the environment accelerated markedly after the 1950's (Steffen, 2004). Under widely accepted consumption projections, in 2050 humanity will be using an amount of resources which is 2.6 times higher than can be renewed, although global bio-capacity is expected to rise only until 2030, partly as an effect of global change (Moore et al., 2012).

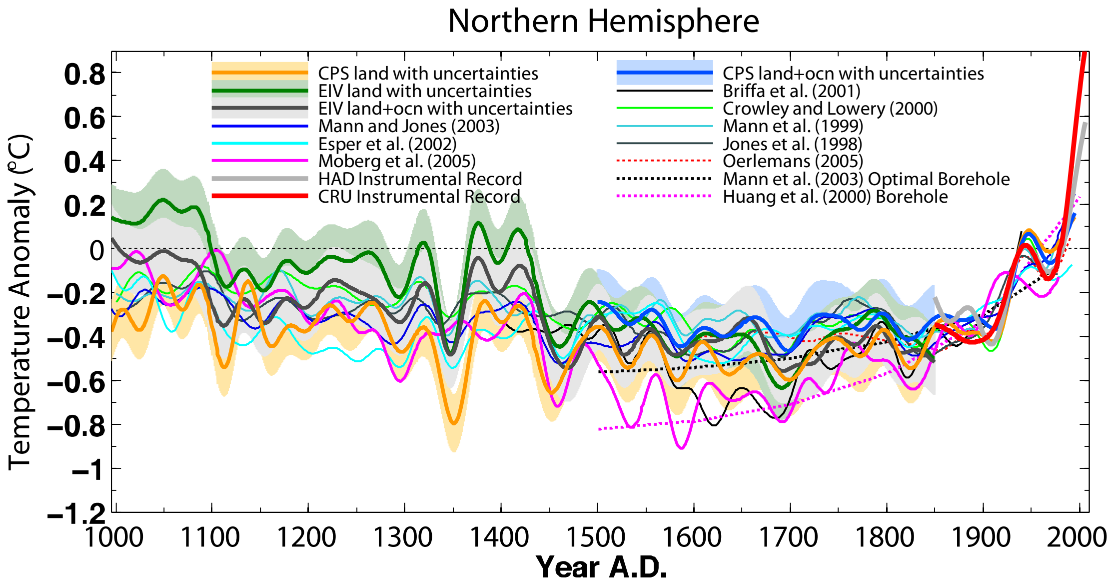

Figure 1: Composite plus scale (CPS) and "error-in-variables" regression (EIV) of northern hemisphere land and land plus ocean temperature reconstructions and estimated 95% confidence intervals, illustrating the "Hockey Stick" shape and exceptional recent climate warming from Mann et al.(2008).

Recently, the question was raised if human activities have now reached a magnitude, substantiating the exclamation of a new geological epoch, expressed as the Anthropocene (Zalasiewicz et al., 2011), which was popularized by the chemist and Nobel Prize winner Paul Cruzen. In 2008, a proposal was presented by members of the Stratigraphy Commission of the Geological Society of London, to accept the Anthropocene as a formal geological epoch after the Pleistocene (Zalasiewicz et al., 2008). Indeed only our influence on the global carbon cycle could justify a new epoch in the opinion of Raupach and Canadell (2010). They identify two fundamental roles which carbon plays in the evolution of the Anthropocene. Firstly, the CO_2 emissions causing climate change are addressed and secondly, exploitation of detrital carbon provides an essential evolutionary trigger. Michael E. Mann et al. (1998) published a paper on global-scale temperature patterns and climate forcing over the past six centuries in Nature which led to the "Hockey stick controversy" since their data suggest recent exceptional climate warming. The authors used a combination of several methods and data sources which led to controversial discussions. Unfortunately, it seems that their estimates are correct and updates have been published in 2003 (Mann et al., 2003) and more recently in 2008 (Mann et al., 2008, see Figure 1).

Peak everything or peak us: what comes first?

There is no doubt that exponential growth is impossible on a finite planet and scientific discussions about the peak supply of a given resource are as old as the utilization of the respective resource. The term "peak oil" was first introduced by Marion King Hubbert (Hubbert, 1949), who realized that oil field production could be roughly described using a logistic distribution and thus peaking at a given time when the maximum production is reached. Oil discovery and production is shaped by a number of factors that make future supply predictions difficult, but there are signs that the global production peak may approach sooner than indicated in the IEA World Energy Outlook (Sorrell et al., 2012). Today, the term is widely used for a great number of resources, especially for raw ores, but even for renewable commodities such as timber from tropical forests, caused by over harvesting and the common implementation of non-sustainable "management" practices (Shearman et al., 2012).

The growing world population and finite resources leads to serious problems, for example 925 million humans are malnourished (FAO, 2010). Interventions in family planning on national levels, e.g. by enforcing the use of condoms as suggested by Pimentel and Pimentel (2006) might not be an ultimate solution. However, as they correctly state, the energy efficiency of current systems must be dramatically increased. Here I assume that state interventions might be more effective by an order of magnitude. The dynamics of world population growth and associated scarcity in resources depends largely on the actual demographical trends. On the other side, there are good indicators that the world's population growth will come to an end in the current century (Lutz et al., 2001).

Technological development is progressing, which implies a number of positive effects e.g. rise of efficiency or transition to renewable resources and energy. These thoughts lead me to an analogy, presented at a recent conference we organized in Vienna in 2007, where Rudy Rabbinge presented a slide stating: "…the stone age did not end because the supply of stones was ending…" (Rabbinge, 2007).

Energy, Resources and the Environment[1]

Motivation for the current dissertation is based on the idea of a sustainable future energy system and the utilization of biomass as an alternative source of energy with a focus on carbon emissions reduction. Our current energy system is mainly based on carbon intensive metabolisms, resulting in great effects on the earth's biosphere. The majority of energy sources are fossil (crude oil, coal, natural gas) and release CO_2 in the combustion (oxidation) process, which takes place during utilization of the energy. Carbon released to the atmosphere from these sources was sequestered over a time span of millions of years and is now being released back into the atmosphere within a period of just decades. Fossil energy is relatively easy to harvest and use and therefore has been fuelling the world economy since the industrial revolution. Fossil fuel emissions are still increasing despite a slight decrease in 2009 as a consequence of the world's economic crisis. Recently, the increase is driven by emerging economies, from the production and international trade of goods and services (Le Quere et al., 2009).

"If we don't change direction soon, we'll end up where we're heading" is the headline of the first paragraph in the executive summary of the World Energy Outlook 2011 (International Energy Agency, 2011b). It exposes systematic failure of combating climate change and the emphatic introduction of a "green society", leaving the fossil age behind. Certainly such far reaching transformations would take time, but recovery of the world economy since 2009, although uneven, again resulted in rising global primary energy demands (International Energy Agency, 2011b). It seems that more or less ambitious goals for climate change prevention are only resolved in phases of a stable economy. Atmospheric carbon dioxide (CO_2) is the second

1 The author is board member of the eponymous Division 7 of the European Geosciences Union (EGU) and holds the position as "Scientific officer for surface processes".

most important greenhouse warming agent after water vapour, corresponding to 26% and 60% of radiative forcing, respectively (Kiehl and Trenberth, 1997). Together with other greenhouse gases (GHG's; e.g. methane (CH_4), nitrous oxide (N_2O) or ozone (O_3)) they contribute to anthropogenic global warming. Climate change occurred a number of times in earth's history. The driving forces were not anthropogenic and mostly caused by Earth's orbital, lunar or volcanic anomalies but in some cases still had a biological origin. In a recent correspondence in Current Biology, Wilkinson et al. (2012) speculates if sauropod dinosaurs methane emissions helped drive Mesozoic climate warmth. Their results suggest that sauropod dinosaurs had a potentially considerable influence on the climate via their flatulences with associated methane emissions.

65 Ma years later, industrialization is driven by fossil sources of energy, emerging in the 17th and 18th century in England as a historical singularity, but soon spreading globally. Today, our economies still rely on relatively cheap sources of fossil energy, mainly crude oil and natural gas, and are consequently emitting as much as 10 Pg C per year in 2010 (Peters et al., 2012). The most comprehensive and longest continuous monitoring of atmospheric CO_2 concentration has been carried out by the Mauna Loa Observatory in Hawaii, publishing the well-known Keeling Curve (see figure 2), representing the dynamic change since 1958.

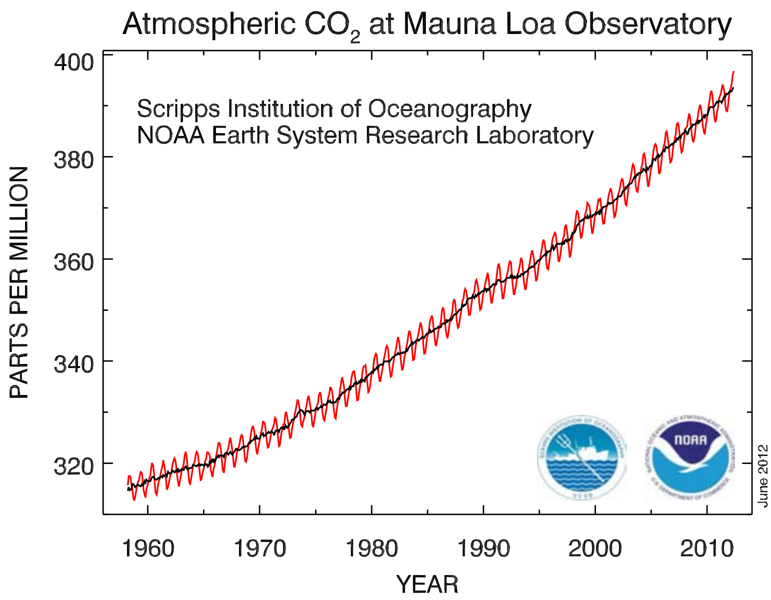

Figure 2: Atmospheric CO_2 at Mauna Loa constitute the longest record of direct CO_2 measurements in the atmosphere. It is often referred to as the Keeling Curve, since David Keeling started the observation in March, 1958. Source: Tans (2012).

Observing the Keeling Curve, one can easily recognize the seasonal variability which is directly triggered by CO_2 uptake of the vegetation in the northern hemisphere during the vegetation period and secondly, which is even more important in terms of global change, a steady increase of CO_2 concentration from 315 ppmv in 1958 to 394 ppmv in March 2012 (Tans, 2012). Earlier concentrations have been derived from air occluded in ice cores. Neftel et al. (1985) presents accurate gas concentration measurements for the past two centuries. However, the theoretical knowledge of the warming potential of CO_2 in the atmosphere evolved in the late 19th century. A theory of climate change was early proposed by Plass (1956), pointing out the "Influence of man's activities on climate" as well as the CO_2 exchange between oceans and atmosphere and subsequent acidification. He highlighted the radiative flux controlled by CO_2 in the 12 to 18 micron frequency interval, agreeing with a number of studies published in the forthcoming decades, e.g. Kiehl and Trenberth (1997). In order to understand the fate of anthropogenic CO_2 emissions, research soon focussed on estimating sources and sinks as well as their stability, since it was obvious that the atmospheric concentrations did not rise at the same magnitude as emissions. Available numbers on current fluxes are principally based on the work of Canadell et al., (2007) and Le Quéré et al., (2009). In their studies, it is emphasized that the efficiency of the sinks of anthropogenic carbon is expected to decrease. Sink regions (ocean and land) could have weakened, source regions could have intensified or sink regions could have transitioned to sources (Canadell et al., 2007). Another explanation might be the fact that the atmospheric CO_2 concentration is increasing at a higher rate than the sequestration rate of sinks (Le Quere et al., 2009). Moreover, CO_2 fertilization on land is limited as the positive effect levels off and the carbonate concentration, which buffers CO_2 in the ocean steadily decreases (Denman, K.L. et al., in Le Quere et al., 2009). As a consequence, the sea water pH value will decrease at an estimated 0.14-0.35 units during the 21st century (IPCC, 2007). This endangers the habitat of coral species, in particular hard corals, which rely on carbonate that is incorporated in their tissue. A recent study concludes that additional CO_2 uptake by oceans also threatens fish populations in reduced recruitment success, as well as higher activity coupled with riskier behaviour of larvae and consequently a higher mortality from predation (Munday et al., 2010). Fossil fuel combustion and land use change (LUC) are the major sources for anthropogenic carbon emissions. Land use change is usually associated with agricultural practices and intensified agriculture triggers deforestation in developing countries (Lambin and Meyfroidt, 2011) and consequently causes additional emissions.

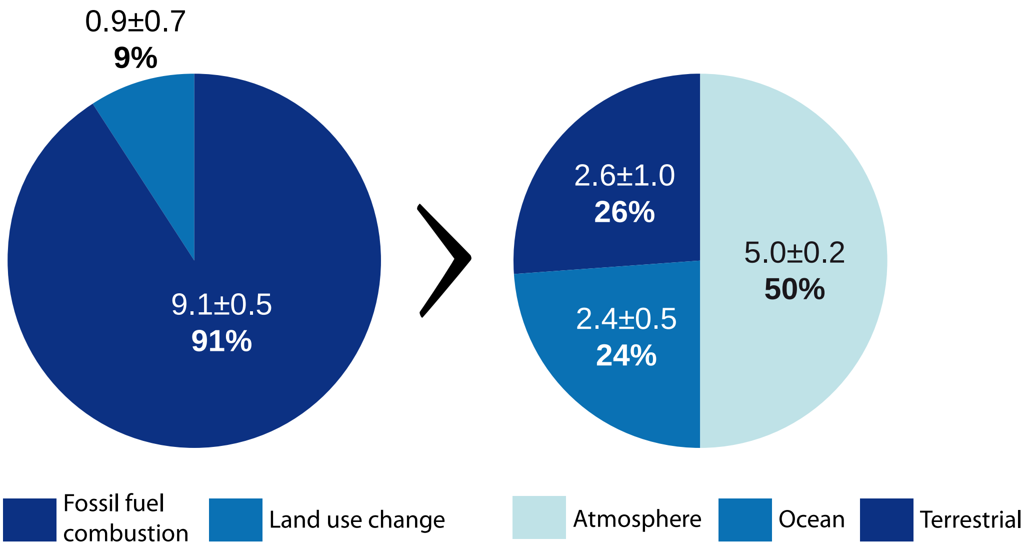

Figure 3: The fate of anthropogenic CO_2 emissions in 2010, showing sources (left) and sinks (right). Presented numbers are Pg C yr^{-1}. The values for 2010 were presented at the Planet under Pressure 2012 conference in London (Peters et al., 2012).

Could nuclear fission energy mitigate the greenhouse problem?

There is currently only a single non-renewable source of energy which holds a considerable share of the global energy portfolio and which is generally disconnected from the C cycle. Nuclear fission energy is propagated to be CO_2 neutral and therefore environmentally friendly. Despite the fact that world-wide resources of uranium are finite, its natural occurrence is extremely diverse (Cuney, 2009) resulting in increasing exploration costs as lower grade substrate must be considered for mining. Nevertheless, fission energy could reduce C emissions by nearly 40% of what is needed to limit the temperature increase to a maximum of 2°C within the period 2025-2065 (Knapp et al., 2010). Nuclear Energy is seen to be the most practical option for low C development in the case of the United Arab Emirates (UAE), even when compared with renewable resources according to a recent study (AlFarra and Abu-Hijleh, 2012). Based on a single literature citation, which is entitled "Nuclear Engineering Handbook" (Kok, 2009), they argue that solar power is more expensive and thus not competitive. Although a recent meta-analysis confirms their statement, it shows that wind energy has, among the renewable resources a higher return on investment (EROI) as compared to

nuclear sources (Kubiszewski et al., 2010). Nuclear wastes production and issues of safe long-term storage and treatment as well as immanent risks of fission technology are not considered at all by the authors.
A 9.0 magnitude earthquake and the subsequent tsunami caused one of the most severe nuclear accidents in the history of civil utilization of fission. A nuclear meltdown at the Fukushima Daiichi reactor released large amounts of radioactive nucleoids into the environment (Shozugawa et al., 2012), polluting landscapes for decades. Although the direct impact was lower as compared to the Chernobyl incident as much of the radioactive material was deposited over the Pacific Ocean, threats to human life comes from fine dust particles acting as alpha ray emitters. If taken up by organisms via food or air, fine particles might be incorporated into living tissue, continuously emitting alpha rays and as such facilitating development of DNA damage and associated diseases, e.g. cancer (Simmons, 2001). The German government quickly reacted as a consequence of public pressure, probably catalysed by long-term consequences of the previous incident in Chernobyl. All atomic power plants will be closed down by 2020. In contrast to Japan, fission energy was always heavily debated in Germany which may have eased this decision. In Japan, the long-term energy strategy has focussed on an increase of the share of nuclear power (Huenteler et al., 2012). In this context, the Fukushima incident had a profound impact on Japan's future energy plans. It was decided to reconsider the "Basic Energy Plan" and reduce dependence on fission power instead of a pre-Fukushima projected increase in fission (METI, 2011 in Huenteler et al., 2012). This clearly demonstrates the vulnerability of fission power as a considerable share of the future energy system. Incidents, such as Chernobyl, Three Mile Island or recently Fukushima demonstrated the massive long-term consequences on large areas. Society must decide if such risks are acceptable, but there is a general trend of rejection and it might be difficult to focus on nuclear fission as a solution for CO_2-neutral energy provision. There are a number of alternatives with much lower risks for environment and human health. Solar radiation, for instance, has a large potential to provide safe energy with low emissions (during production and setup of components) and it could be directly (heating, photovoltaic) or indirectly (3rd generation biofuels) converted into energy.

The challenge to introduce a low-carbon emitting society – Kyoto protocol quo vadis

The United Nations Conference on Environment and Development (UNCED), which was held in Rio de Janeiro 20 years ago, aimed at addressing environmental and associated social problems in a wider context. One of the outcomes was the United Nations Framework Convention on Climate Change (UNFCCC), an international treaty. Since it entered into force, annual meetings (Conference of Parties, COP) are scheduled and COP3, held in Kyoto in 1997, produced an update for the UNFCCC which is known as the Kyoto Protocol. Since the UNFCCC itself sets no mandatory limits on GHG emissions, the Kyoto Protocol was necessary to provide a framework which ensures binding targets based on international law. The Kyoto Protocol entered into force in 2005. It aims at a reduction of GHG emissions by five per cent based on national levels of 1990 either by limiting fossil fuel consumption, by increasing terrestrial C sequestration or both. Inherent mechanisms allow countries to transfer emission certificates among themselves or to earn credits from reduction projects in developing (non-Annex 1) countries via the Clean Development Mechanism (CDM). As such, it is the most comprehensive binding multinational agreement to mitigate climate change (International Energy Agency, 2011a) and it takes into account the role of the developed countries as the major perpetrator of current GHG levels. The major achievements of the protocol, for instance the establishment of a global response to the climate change problem, the stimulation of an array of national policies, the creation of an international carbon market and the establishment of new institutional mechanisms may provide a good foundation for future mitigation efforts (IPCC, 2007). However, it implies action on less than one-third of global CO_2 emissions, as measured in 2008 (International Energy Agency, 2011a). Despite the uncertainty in calculating GHG emissions (Gupta et al., 2003), the protocol itself is criticized and its ability to substantially reduce GHG emissions is questioned. According to a recent investigation, Kyoto mechanisms are merely encouraging increased installed capacity of existing technologies instead of

creating incentives for more sustainable variants of renewable technologies in the BRICS countries (Bodas Freitas et al., 2012). Nabuurs et al. (2008) argue that incentives to enhance the biomass production in forests are only created through specific management actions which do not secure sustainable forest management for climate change mitigation and it does not take into account the specific situation in each location. Moreover it is a fact that Kyoto reforestation projects cover a time frame of less than 20 years, which could be sufficient to recover aboveground carbon stocks but it is too short to observe significant belowground carbon trends. Soil carbon pools react slowly and on lower magnitudes as compared to aboveground pools (Bruckman et al., 2011) and it is unlikely that it will be possible to monitor any clear effects of management-related changes e.g. in broadleaved tree species (Vesterdal et al., 2008).
Carbon footprints have become the currency of a climate constrained world and they are strongly linked to ecological or environmental footprints (Cranston and Hammond, 2012) and hence a key issue of the Kyoto protocol. They consist per definition of the total emission of GHG that cause climate change by a unit (e.g. person(s), building, country) or a specific action (e.g. event, journey, construction). The problem of the Kyoto protocol in context of the carbon footprint is that it only accounts for domestic emissions. Hence a country's carbon footprint and its domestic CO_2 emissions need not coincide (Aichele and Felbermayr, 2012). International trade has shifted a great amount of emissions in developed countries to developing nations and Aichele and Felbermayr (2012) conclude that the Kyoto protocol has at best no effects on worldwide emissions. Footprint analyses might therefore be a good indicator to account for GHG emissions for a specific unit or action, regardless of scale and national boundaries. In order to track anthropogenic pressure on our planet it is insufficient to consider a single footprint value, as for instance the carbon footprint. At least the water footprint and the ecological footprint have to be considered for a holistic and interdisciplinary view. Galli et al. (2012) tried, for the first time, to integrate the three above mentioned footprints into a "Footprint Family" of indicators, providing a tool for policy makers and researchers to facilitate an integrative impact assessment while eliminating misconceptions and misunderstandings of footprint indicators and their messages and range of application.
There is evidence for both the success and the failure of the Kyoto protocol. Perhaps the indirect effects are the most efficient and successful components of the protocol, which brought governments together, considering their emissions and raised public awareness. Even if the direct intention was unsuccessful in curbing emissions, it has initiated a magnitude of actions which might not have been initiated if the UNFCCC's Kyoto protocol was not implemented. Since the commitment period of the Kyoto protocol ends this year, it is inevitable to deeply analyse weaknesses and seriously consider criticism in order to finally come up with a better solution for the next commitment period. Although this could be a difficult task with the background of weak economies and international debt crises, the costs of doing nothing are equal to an annual loss of between 5 and 20% of the global GDP, according to the Stern Review on the Economics of Climate Change (Stern, 2006). In view of the underlying facts, it seems that there is no choice but to act.

The role of forests as carbon sinks

Forest soils represent the largest terrestrial C pool (Jobbágy and Jackson, 2000) because forests are the dominant vegetation in non-desert areas of the globe. Hence even small changes have the potential to significantly alter atmospheric CO_2 concentrations (Diochon et al., 2009). Jobbágy and Jackson (2000) estimated that global forest soil C stocks down to three meters soil depth represent 1 104 Pg C, which is considerably more than the 704 Pg presented in the IPCC report (Prentice, 2001) respectively 787 Pg down to one meter soil depth (Dixon et al., 1994). Here it becomes obvious that different approaches and model assumptions yield different results and more research is urgently needed to describe worldwide SOC pools. It is also shown that subsoil horizons have a large SOC storing capacity, despite the fact that most studies investigating SOC pools concentrate on topsoil layers because of the rising effort and cost of sampling deeper soil horizons. The importance of considering subsoil horizons when studying soil C has recently been pointed out (Hamburg, 2000; Diochon et al., 2009). On average, two-thirds of the total C in forest ecosystems are stored in the soil (Dixon et al., 1994). Sequestration of CO_2 in forests is controlled by environmental conditions, disturbance and management. However, forests can act as a source or sink of C, depending on the balance between photosynthesis and respiration, decomposition, forest fire and harvesting operations, while on both European and global scales, it is confirmed that forests were estimated to act as sinks on average over the last decades. (Vetter et al., 2005; Nabuurs et al., 2008). Our current forests are capable of sequestering ~2.4 Pg C yr^{-1}, excluding tropical land-use change areas (Pan et al., 2011).

A question for a forest owner in terms of carbon sequestration is which management option to choose while still being able to produce products and generate income. Despite the fact that unmanaged forests hold the highest C pools, it was commonly believed that aggrading forests reach a maximum sequestration and it is reduced in old growth forests, where photosynthesis and autotrophic respiration are close to offsetting each other. This is in contrast to a number of studies, pointing out that even unmanaged forests at a late successional development stage could still act as significant carbon sinks (Schulze et al., 2000). The authors of another study claim that advanced forests should not be neglected a priori from the carbon sequestration discussion (Knohl et al., 2003) and they should be left intact since they will lose much of their C when disturbed (Luyssaert et al., 2008). Therefore, managing forests implies a trade-off between maximum C sequestration and provision of goods, such as timber and biomass for energetic utilization. While the highest amounts of carbon could be stored in unmanaged forests (Luyssaert et al., 2008; Schulp et al., 2008), targeted additional C sequestration through forest management can be a cost-effective way to reduce atmospheric CO_2, despite limited quantities, due to biological limitations and societal constraints (Seidl et al., 2007). This is in general agreement with the conclusion of Wiseman's (2003) dissertation, who argues that there is potential for additional C uptake depending on forest management, but the effect is short-term until a new equilibrium in C stocks is reached and he also argues that the effect may be limited. Jandl et al. (2007) argue that there are two major ways to increase C sequestration in a managed forest. Firstly, enhanced productivity sequesters more C in the aboveground biomass and subsequently in soil and secondly, stable forests are less prone to disturbance which might releases substantial amounts of C. The authors particularly mention the potential of mixed species forests to enhance stability. Enhanced productivity is either achieved by selection of species with high NPP or by fertilization. Particularly N fertilization has the potential to increase NPP and thus C sequestration (discussed below) but also other trace elements eventually contribute to increased NPP (Lal, 2005), based on the actual nutritional status of the forest site. Another factor influencing the total C budget is the use of forest products. C from forest biomass, particularly from construction or furniture wood, might not be immediately released to the atmosphere and therefore contributes to sequestration. Consequently, a recent study suggests that forest management sequesters more aboveground-carbon than forest preservation over a time span of 40 years if the wood is used for products with an average half-life greater than 5 years (Van Deusen, 2010). LUC might be the most efficient way to sequester additional C, e.g. by afforestation of marginal land (Chang et al., 2012), meadows or degraded agricultural land (Lal, 2005), but the potential in Europe is limited by environmental and political constraints (Jandl et al., 2007) and the effect is very site-specific, particularly in the subsoil (Poeplau and Don, 2012). Even bioenergy crops have the potential to sequester additional C, which was earlier demonstrated (Matthews and Grogan, 2001). Soil C cycling can be divided into three major interacting components (Grandy and Neff, 2008):

1. The deposition of chemically distinct compounds (aboveground and belowground litter)
2. Decomposition by soil fauna, bacteria and fungi by extracellular enzymatic activity and through assimilation (and re-deposition) of C compounds as microbes die
3. The physical redistribution and stabilization of carbon in the soil, including transport, sorption and aggregation of soil particles

C sequestration is achieved by net primary production which is a result of photosynthesis, i.e. the chemical transformation of atmospheric CO_2 and water from the soil matrix into more complex carbohydrates and long chain molecules. They build up cellulose which is found primarily in cell walls of woody tissue as well as hemicellulose and lignin. C remains in the woody compound until it is either degraded by microorganisms, which use it as source of energy, or until oxidation takes place (e.g. burning biomass, forest fire). In both cases, it again becomes part of atmospheric CO_2. A certain share of organic matter (OM), controlled mainly by climatic conditions (Bruckman et al., 2011), enters the soil pool as soil organic matter (SOM). It is then being degraded during the decomposition process and enter the SOC pool. The ratio between aboveground and belowground C pools depends on the current stand age, forest management and climate. In temperate managed forests, SOC stocks are typically similar to the aboveground stocks (Don et al., 2012), which is confirmed in our own research (Bruckman et al., 2011). SOC (and in particular O-horizon) stocks are typically high in boreal forests and in high elevation coniferous forests as a consequence of low degradability of perennial foliage, reduced microbial activity and low in most tropical environments. Especially O-layer C pools are sensitive to changes in local climate. A traditional forest management regime in Austrian montane spruce forests is clear-cut, typically from the top of a hill to the valley to facilitate cable skidding. An abrupt increase of radiative energy and water on the soil surface creates favourable conditions for soil microorganisms and a great amount of C stored in the O-layer is released to the atmosphere by heterotrophic respiration. Other GHG's, such as N_2O are eventually emitted under moist and reductive conditions as excess nitrogen is reduced under anoxic conditions. Unfortunately, this effect is likely to happen on a large-scale where massive amounts of C might be released as the global temperature is rising and permafrost thaw induces C emissions (Schuur and Abbott, 2011), potentially creating a strong feedback cycle, further accelerating global warming. However, Don et al. (2012) found that SOC pools were surprisingly stable after a major disturbance (wind throw event), indicating low short-term vulnerability of forest floor and upper mineral horizons. They explained their findings with herbaceous vegetation and harvest residues, taking over the role of litter C input. The study covers a time-span of 3.5 years which might be too short to observe soil C changes. Likewise, we did not observe significant C stock decrease in our youngest sample plot of the coppice chronosequence (Bruckman et al., 2011). We expect that N dynamics might have a profound influence on C retention (discussed below) and the impact of disturbance on SOC pools depends on environmental conditions.

Successful long-term sequestration in terms of climate change mitigation is therefore only achieved if C becomes part of the recalcitrant fraction in the (sub)soil, which is typically between 1 000 and 10 000 years old (Rumpel et al., 2002; Schmidt et al., 2011). The C contents are lower in the subsoil, but considerable amounts can still be found if one not only analyses the topsoil layer as recommended by a number of authors, e.g. by Diochon et al. (2009). In contrast, the radiocarbon age of the topsoil may range from less than a few decades (Rumpel et al., 2002) to months if considering freshly decomposed OM. The reasons for the relatively high age in subsoil horizons are not entirely clear, but unfavourable conditions for soil microbial diversity and strong association of C with mineral surfaces (organo-mineral interactions with clay minerals) might be an explanation (Schmidt et al., 2011). When C enters the soil system, it is immediately metabolized and hence the total mass decreases. A certain share enters the recalcitrant pool, while the rest becomes part of the labile pool and eventually returns to the atmospheric pool by respiration. However, there are several mechanisms of stabilizing C in the soil as summarized by Trumbore (2009):

1. Climatic stabilization (e.g. freezing, excess moisture, too little moisture)
2. Intrinsic recalcitrance (e.g. pyrolized carbon, specific lipid compounds)
3. Physical stabilization (association of organic compounds with aggregates or mineral surfaces, e.g. organo-mineral compounds)
4. Inhibition of microbial activity/inaccessibility (abundance of microbial communities, barriers to the interaction of extracellular enzymes with substrate)

The transformation process of C during decomposition depends on a variety of factors, from environmental conditions to the abundance of microbial communities and input compartments. It is a very complex interdisciplinary process and common analytical techniques influence the results, often resulting in operational rather than functional definitions of carbon structures (Grandy and Neff, 2008).
There are in principal two pathways of sequestering C in forest soils. Forest litter consists of leaves, needles and woody debris, such as branches, bark and fruit shells which accumulate on the surface (L and F layer). Soil macrofauna degrades it until it becomes part of the OM where it is impossible to recognize its original source (H layer). Parts of it are translocated into deeper horizons by bioturbation (e.g. earthworms) or remain on the surface, to be further degraded by soil microorganisms while OM becomes mobile in form of humic acids and subsequently being mineralized at a range of negatively charged surfaces (humus, clay minerals). The second pathway is trough root turnover and rhizodeposition (= excretion of root exudates). Matthews and Grogan (2001) and subsequently Grogan and Matthews (2002) parameterized their models with values of between 50 and 85% of C from the fine root pool which is lost to the SOC pool on an annual basis, depending on species composition and management. This assumption is consistent with another study where 50% of the living fine roots were assumed to reflect real values (Richter et al., 1999). There is evidence that C derived from root (Rasse et al., 2005) and mycorrhizal hyphal turnover (Godbold et al., 2006) might be the most important source for SOC pools rather than from litter decomposition. Since fine root turnover is species specific (Jha and Prasad Mohapatra, 2010), it could be controlled to some extent by species composition at management unit levels.

Soil inorganic carbon (SIC)

Soil inorganic carbon (SIC) is a large C pool with an estimated amount of 950 Pg globally, down to one meter soil depth (Eswaran et al., 2000). It is present as carbonate as calcite and/or dolomite and influences both chemical and physical soil properties. Buffer capacity, soil acidity as well as soil structure are directly affected, resulting in effects on soil microbes and consequently fertility and productivity. Moreover carbonates are strongly entangled in biochemical cycles. However, in terms of C sequestration, less studies deal with SIC than with SOC, probably due to a lack of comprehensive data and spatial distribution patterns. Current methods of assessing SOC pools are predominantly based on combustion approaches where released CO_2 from the sample is directly or indirectly measured. Therefore, the result represents the total C (C_t) content of the respective sample. If it contains SIC, it has to be subtracted from Ct in order to derive SOC. SIC may be classified as lithogenic inorganic C (LIC) and pedogenic inorganic C (PIC), where LIC originates from the calcareous bedrock material and the SIC content in the soil remains unchanged. PIC is formed by dissolution and precipitation of carbonate from the parent material while one mole of atmospheric CO_2 is bound during dissolution and liberated during pedogenic precipitation (Wu et al., 2009). C sequestration might also be facilitated by formation of secondary carbonates and by leaching of bicarbonate into the groundwater, thus entering a less active pool (Lal, 2008). Secondary carbonates occur in many forms, e.g. as coatings, films, concretions, threads and pedants and coatings on the lower surface of stones and pebbles is common in calcareous soils with coarse material and they are formed in the pH range of 7.3-8.5 if sufficient Ca^{2+} and Mg^{2+} is available (Lal, 2008). Four principal mechanisms of secondary carbonates formation are described (Lal, 2008):

1. Dissolution of CO_2 in the surface soil layer, followed by translocation and re-precipitation by Ca^{2+} and Mg^{2+} in the subsoil
2. Capillary rise of $Ca2^+$ from shallow groundwater and re-precipitation in the surface layer
3. *In situ* dissolution and re-precipitation
4. Biogenic formation through the activity of soil fauna (Which is expected to occur in some of our study sites)

The Chinese loess plateau covers a large area in central China in the upper and middle reaches of the Yellow River. The soil is very fertile, but over-grazing and deforestation led to increased erosion. Hence reforestation projects were initiated which are well progressing, particularly during the last decades. The effect of afforestation on SOC and SIC pools (*Robinia pseudoacacia* L.) was recently studied and the main results indicate that SOC was expectably increasing due to litter input (aboveground litter and fine root turnover). Interestingly, there seems to be an on-going translocation of SIC to subsoil horizons, triggered by soil fauna activities, root biomass and leaching with subsequent precipitation (Chang et al., 2012). Although we do not have a direct comparison with cropland in our studies, it seems that a similar translocation process took place at some of our plots; particularly on Chernozems (see paper 1).

Nitrogen – a proxy for the carbon cycle?

The fate of C turnover and its allocation into various pools is strongly controlled by nitrogen (N) availability and cycling via biological processes such as biomass production and decomposition. N is one of three macronutrients (nitrogen, phosphorus and potassium) and is an essential component of all proteins. It is commonly the limiting element for plant growth in forest and agriculture systems because of its mobility and absence in most bedrock materials. Plants generally favour nitrate uptake, but also other forms of nitrogen are taken up (e.g. ammonium or amino acids from the dissolved organic matter fraction), based on species-specific requirements and preferences as well as abundance and accessibility. Most of the organic N is found to occur as peptide-like compounds in soils and as such plays a key role in C sequestration since these compounds are important for soil organic matter (SOM) formation (Knicker, 2011). Narrow C/N ratios in mature organic matter, as is the case in our samples indicated in Bruckman et al. (2011), is an indicator for the impact of soil organic nitrogen (SON) even on recalcitrant fractions of SOC (Knicker, 2011). However, there are still considerable knowledge gaps especially on a global scale (Gärdenäs et al., 2011), which is of crucial interest in order to model ecosystem behaviour (e.g. in regard to net ecosystem productivity (NEP) or GHG release) under conditions of global change. NEP is directly related to available N for plant growth and microbial metabolism. N interactions are still under debate since it is subject to continuous transformation processes in soil and biomass as shown in figure 4. An intrinsic property of N is its relative mobility, resulting in immediate leaching if it is not taken up by plant roots or bound by the soil matrix. Groundwater in agriculture dominated landscapes is often contaminated with nitrate which is a direct result of N fertilization. Similar effects may occur in forest ecosystems after major disturbances such as wind-throws or clear-cuts where large amounts of N are mineralized and leached to streams, interfering with aquatic habitats. Rapid decomposition of the foliage of spring geophytes may also induce nitrate flushes in the soil of deciduous broadleaf forests (Jandl, 1991). Compounds composed primarily of N are found in elevated concentrations following clear-cuts in streams associated with the respective catchment area (Rosén et al., 1996).

The Anthropocene is characterized by rising concentrations of CO_2, while N depositions, mainly as inorganic aerosols, are high in industrialized countries and agriculture dominated regions. C sequestration in soils is correlated with N retention. This ultimately leads to the question of effects on forest growth and C sequestration to develop scenarios based on future deposition and CO_2 concentration estimates. Indeed, there are hints of a positive effect on plant growth, both resulting from elevated ambient CO_2 (Gedalof and Berg, 2010) and N deposition, but the processes are too complex to provide a simple answer. Likewise, a meta-study was presented during a conference on "Biological Reactions of Forests to Climate Change and Air Pollution", organized by IUFRO working group 7.01.00 in Kaunas, Lithuania in May 2012, pointing at positive growth effects by both N deposition and CO_2 fertilization. However, the latter might be limited by N availability (Kongoi et al., 2012). The additional C sequestration as a factor of increased N deposition was estimated to be 10% of total sequestration in European forests during the period of 1960-2000 (De Vries et al., 2006), while central Europe played a major role in comparison to northern and southern Europe. In contrast, China has experienced massive N deposition rates especially in the south-eastern region where amounts of more than 40 kg ha yr^{-1} are reported (Lu et al., 2011). The authors estimated that N-induced C sequestration accounts for more than 25% of China's emissions from burning fossil fuels between 1901 and 2005. However, the efficiency of N use has levelled off since the 1980's, indicating a saturation effect. Therefore further deposition should be minimized to avoid negative environmental impacts, such as soil acidification or emission of N_2O.

The idea of fostering carbon sequestration in forests has recently brought forth questionable new developments. At a session on enhanced carbon sequestration in the terrestrial biosphere at the European Geosciences Union (EGU) General Assembly 2012, it was argued that there should be additional harvests which are then buried in the forest soil in order to obtain a "semi-permanent" carbon sink (Zeng and Zaitchik, 2012). Perhaps climate change mitigation sometimes seems as simple from the view of a climatologist, but they entirely ignored consequences of harvest increase, large scale soil disturbance and economic implications. Climate change mitigation could be achieved from another approach as well, which might be far more efficient: changing our lifestyles and hence reducing emissions.

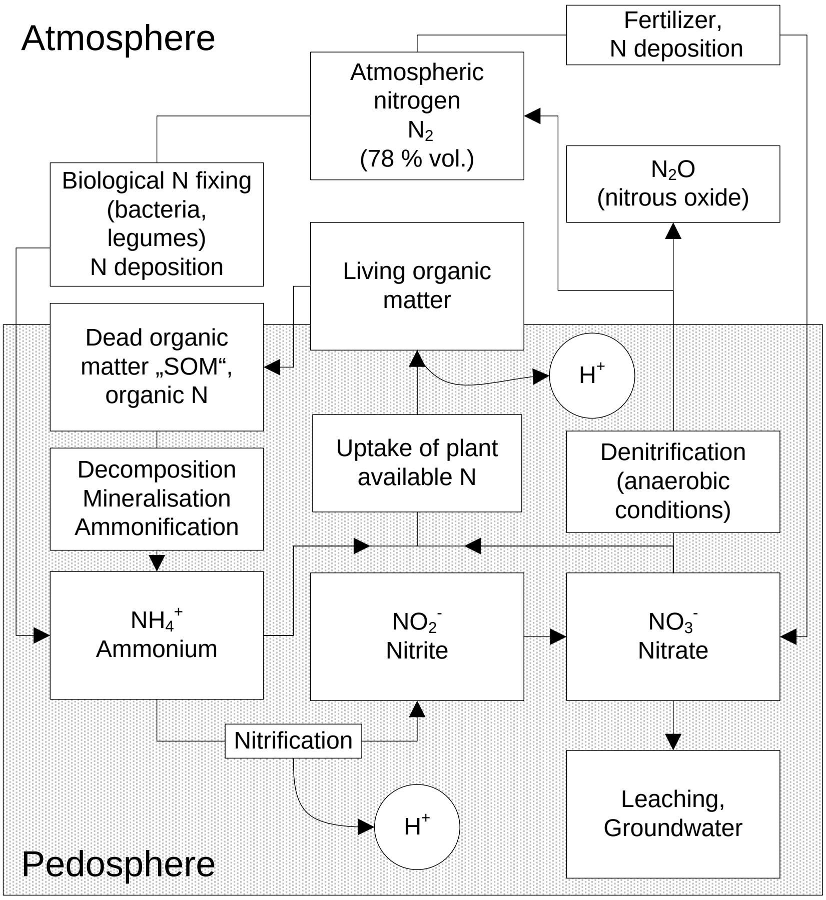

Figure 4: A rough and simplified conceptual model of N metabolism in a forest ecosystem, considering both aboveground and belowground processes. This figure was modified from Hochbichler et al. (2009).

REDD: A forestry-based framework to mitigate climate change

Forests are the largest terrestrial C sink and consequently play an important role in climate change mitigation strategies. Recent estimates suggest that forests could account for a terrestrial C sink of ~2.4 Pg C yr^{-1} (Pan et al., 2011). In their study, Pan et al. (2011) emphasize that the tropics are dominant in terms of terrestrial-atmospheric CO_2 exchange but the major problem in the tropics is still deforestation as a consequence of LUC. Undoubted, human activities have a strong impact on carbon pools in both managed and unmanaged forests in the tropics (Djomo et al., 2011). This consequently highlights the significance of the United Nations Reducing Emissions from Deforestation and Degradation (REDD) program, according to the authors. REDD was developed from a proposal of the Coalition of Rainforest Nations led by Papua New Guinea in 2005 and was added to the agenda at the 2007 COP13 conference of the UNFCCC in Bali. It is in principal a market based incentives mechanism with transfers expected from developed to developing countries, or in other words, rich nations pay for reduced deforestation and land degradation in tropical countries. REDD has become popular in the last few years and recently, REDD+ is a common term adding additional benefits besides reduced deforestation and degradation. The main goals of REDD+ are:

1. enhanced carbon sequestration
2. commodification of carbon
3. economic development and
4. forest conservation

Currently, the REDD+ mechanism is facing systematic problems, such as a leakage from timber harvest and deforestation from signatory to non-participatory countries (Lambin and Meyfroidt, 2011) which will not be solved until all (tropical) countries participate. However, at this point it is not clear if deforestation and degradation is then on-going beyond tropical regions. Therefore, it is crucial to attract as many nations as possible to participate since REDD+ offers a magnitude of benefits even for countries with a comparatively low forest cover. South Africa, for instance, has as little as 1.3% forest cover but the land use and forestry sector actions could include degraded forest restoration, improved productivity associated with reduced GHG emissions in agriculture and capacity building in forest carbon sequestration (Rahlao et al., 2012). The major problem in developing countries is poor implementation of formal forest management requirements rather than its existence, suggesting that REDD+ should support implementation of existing national and sub-national forest policies in order to maximize its effectiveness (Kanowski et al., 2011). Decisions supported by REDD+ have the potential for a large social impact, hence it is rejected by some indigenous local communities because it implies major restrictions in forest management, even for traditional ways of forest use. In summary, it can be said that there are still problems with the REDD+ mechanism and it must be further modified in order to raise acceptance and minimize risks. Whether REDD+ or similar strategies will benefit or marginalize forest communities ultimately depends on tenure. Local implementation and clear systems of rights, along with participatory approaches and capacity building might be key elements of a successful mechanism which implies long term beneficial effects for local people as well as for global climate change mitigation. Overall, it has to be ensured that C commodification is not misused as a vehicle for business and speculation, obscuring initial aims of reduced fossil fuel use.

Biomass from forests – the smart alternative of C farming?

There is an on-going debate regarding the potential of obtaining biomass from forests for energetic use on multiple scales, from stand to international levels. Biomass is often discussed in the context of a raw material for energetic utilization although it should be emphasized that total biomass figures account for the total harvestable amount of wood, regardless of its utilization or economic value. Especially in the context of energy, it is highlighted that biomass is an entirely CO_2 neutral feedstock since the carbon stored in wood originates from the atmospheric CO_2 pool and it was taken up during plant growth. This is, in principal, true despite biomass from forests is not being free of CO_2 emissions per se, since harvesting and further manipulation requires energy, which is currently provided by fossil fuels. However, it is difficult to estimate per-unit CO_2 emissions since there are many influential variables. Even a single variable could have a profound influence on the per-unit emissions as it is shown for the case of chipped fuel (Van Belle, 2006).

In general, biomass requires a different treatment as compared to fossil sources of hydrocarbons. Chemical transformations over thousands of years under high pressure led to a higher density of yieldable energy per volume unit as compared to forest biomass, although hydrocarbons are ultimately a form of solar energy. Hence existing infrastructure for fossil fuel does not fit to sources of renewable energy because of their different properties. Centralized structures of energy distribution might work for fossil fuels, but it is questionable if it makes sense to transport woodchips across large distances. The energy invested for (fossil based) transport eventually curbs the benefits of renewable energy resources in terms of C emissions.
The aim of the present dissertation is based on exactly such considerations of regional availability of woody biomass from forests. At the time the main project was started, Vienna just launched Europe's largest biomass power plant at that time with a total capacity of 62.5 MW, at an overall theoretical fuel efficiency of 82%. The "Biomass Power Plant Simmering" is designed as a combined heat and power plant (CHP) with scalable yields. The maximum electric power output (during summer) is 24.5 MW, with 37 MW thermal energy provision (Heumesser, 2012). With 19 tons of biomass (chipped wood) per hour, it requires substantial amounts of feedstock, hence a contract was set up with the Austrian Federal Forests (ÖBf AG) on provision of regional biomass, indicating that "…over 80% of the biomass which will be utilized by the CHP Simmering comes from a distance of less than 100 km from Vienna. Less than 20% of the biomass will be transported by rail, ship or trucks from slightly greater distances…" (Österreichische Bundesforste AG, 2005). According to a report of the Austrian Audit Court, ecological aspects were not sufficiently considered regarding feedstock logistics since ÖBf AG planned to provide nearly 100% of the required biomass by means of truck transportation, although the power plant has a direct rail connection (Rechnungshof, 2007).
The Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management funded the project titled "Investigations to the dynamic of the biomass and carbon pools in coppice with reserves stands, coppice with standards stands and high forest stands" in 2007, aiming at assessing biomass pools along with other aims related to silvicultural practices. The current dissertation is based on this project.
Five years later, the initial assumptions on biomass provision turned out to be false, and biomass is provided from a radius of 450 km (Wikipedia, 2012), contradicting recommendations by the Austrian Audit Court (Rechnungshof, 2007) and earlier concepts for feedstock provision. As a result, biomass power plants should be designed at smaller scales, ensuring sustainable regional biomass provision only in regions with sufficient feedstock. It is therefore questionable, if rather technocratic, lobbyist/politics driven approaches of using standard refinery units as a heritage of the fossil age to process biomass (as suggested by Melero et al., 2012) would be a sustainable option. Careful planning of local facilities is required to avoid economic drawbacks, including a profound analysis of the potential customers for energy. For instance, total heat requirements may be lower than expected since newly built homes are usually well insulated and there are a number of funding programmes for improving thermal insulation of existing buildings built to lower standards.
Biomass from forests for energetic utilization is often seen as a by-product of conventional forestry and subsequent industrial processes. Residues from early silvicultural interventions such as thinning; e.g. slash and sawdust are seen as the most important feedstock. This opens the floor for controversial discussions and assumptions, based in principal on ecological and economic concerns. While residuals of thinning operations are requested by traditional industries, (e.g. paper mills) the extraction of slash and other harvest residuals eventually leads to nutrient depletion with ecological impacts and ultimately detriment to increments in the long- term perspective. Inherent soil properties control both magnitude and duration of such developments.
"Residuals" from forestry were traditionally harvested in ancient times. Most of the raw materials extracted from forests served as a source for thermal energy (fuelwood and charcoal) or other feedstock for industrial processes. Moreover, forests in central Europe provided nutrients for agro systems to sustain the human population (Glatzel, 1991). Forest pasture, litter raking and lopping (sometimes referred to as pollarding) are some examples. Since these practices tend to extract compartments with a high nutrient content

relative to wood, soil acidification and nutrient depletion was a common threat in central European forest ecosystems. Nutrient contents of different compartments are shown in figure 5. The N content of foliage, for instance, is eight times higher than that of wood.
Forests only recovered gradually, mainly because of acidic depositions starting from the beginning of industrialization until the late 1980's, when clear signs of forest dieback caused public awareness and subsequent installation of filters across Europe. Today, forest biomass is increasing in most European countries, due to land use change (abandoned mountain pastures, afforestation of marginal agricultural land), shifting tree line as a consequence of global warming and elevated CO_2 concentrations as well as atmospheric N deposition. However, this should not lead to short sighted assumptions that biomass can be harvested at levels of growth increment, since a large part of it grows in areas with unsuitable conditions for access. Easily accessible forests at highly productive sites in lowlands are typically managed at harvesting rates close to increment or even higher e.g. in cases of natural disasters such as wind throws. In some countries, such as Austria, access to specific land ownership structures might uncover greater potentials of additional harvests.

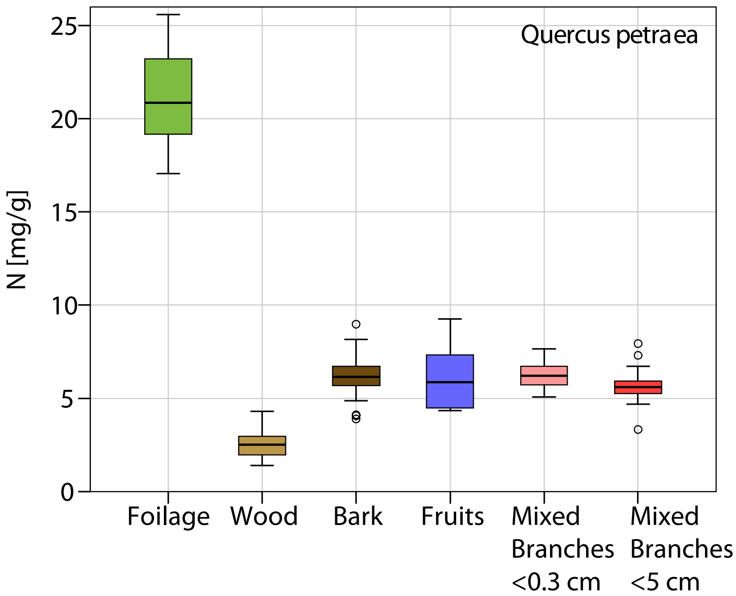

Figure 5: Nitrogen content of different compartments for *Quercus petraea* across all plots of the study location "Hollabrunn". See paper 1 (Bruckman et al., 2011) for more details.

Short rotation woody crops (SRWC)

The major challenges of shifting forest management goals from traditional forestry to biomass production are sustainability issues, relatively low value of the product in comparison to quality logs and expensive harvesting, being competitive only at a high degree of mechanization in developed nations. As a consequence, rotation periods were shortened and fast growing species are preferred in order to produce woody biomass in an agriculture-like manner. Short-rotation woody crops (SRWC) are hence established, typically with fast growing, e.g. *Salix*, *Populus* or *Eucalyptus* species. SRWC is based in ancient times, when people coppiced woodlands in order to obtain raw materials, e.g. fuel-wood for cooking or heating purposes but most of the research was done and application of the results was achieved in the last 50 years (Dickmann, 2006). Planting is optimized for maximum biomass production (increment) while minimizing threats of disease and facilitating highly mechanized harvest technologies. Typical rotation periods are between 1 and 15 years (Dickmann, 2006), and rotations of e.g. willow are shorter than those of poplar. Biomass from short rotation extracts significant amounts of soil nutrients since a higher share of nutrient rich compartments (bark and thin branches) is extracted from the system in comparison to traditional longer rotation systems. Figure 6 illustrates the dynamic nutrient allocation in different compartments along a chronosequence of stand development. Foliage and thin branches are dominant pools for N in early stages of stand development.

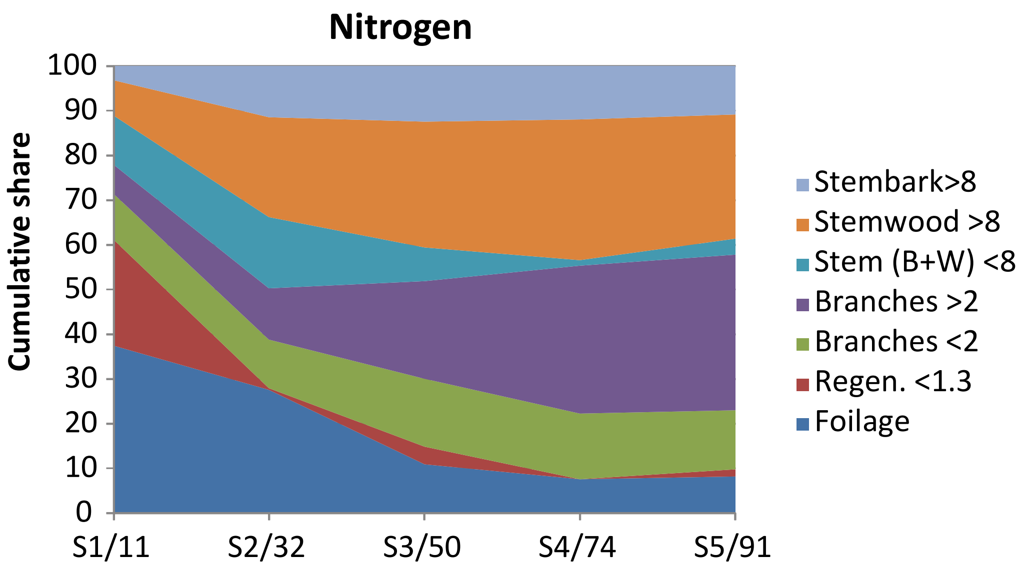

Figure 6: Cumulative share of Nitrogen in different compartments for *Quercus petraea* along a chronosequence in the study location "Hollabrunn". Category explanation (same order as legend): Bark of stems > 8 cm DBH, Stemwood without bark > 8 cm DBH, Stems < 8 cm DBH (wood and bark), Branches > 2 cm diameter (wood and bark), Branches < 2 cm diameter (wood and bark), Regeneration < 1.3 m height (total value), Foliage (living). See paper 1 (Bruckman et al., 2011) for more details about the plots and study location.

Ma et al. (2007) found declining soil nutrient stocks in Chinese silver fir plantations suggesting that successive plantings may result in nutrient shortages despite increasing atmospheric N depositions (as mentioned earlier). This implies the need of fertilization in most cases and concerns e.g. about N leaching into groundwater bodies are discussed. However, Aronsson et al. (2000) showed that high rates of N fertilization do not necessarily prime leaching, even on sandy soils (Eutric Arenosol) if the demand for N is high. C sequestration in the soil is also preliminarily controlled by N fertilization and the response of the vegetation (Garten et al., 2011). The authors found increasing biomass production and C sequestration in a hybrid poplar plantation following N fertilization. On the other hand, it was argued that short rotations eventually result in the loss of the mineralization phase, thus preventing self-regeneration of the forest ecosystem (Trap et al., 2009). Following their argumentation, a rotation cycle should be long enough to permit the return of autotrophic respiration and high rates of mineralization. In terms of C sequestration potential, it ultimately depends on the land use prior to SRWC if and to what extent additional C is accumulated. Especially sites which were formerly used for agricultural purposes and where organic carbon was depleted are prone to additional sequestration after land conversion (Matthews and Grogan, 2001; Grogan and Matthews, 2002). They pointed out that especially, but not only, *Miscanthus* plantations, can substantially sequester C with relatively high amounts of litter. Moreover, perennial plantations are less susceptible to crop failure due to weather extremes. Perennial systems store more C per area in their growing stock.

In a global context, SRWC may interfere with agricultural production if it continues to be a focus and if plantation areas increase since most plantations are not the result of forest land conversion, but rather farmland conversion. One of the reasons for this interference is the varying legal definition of SRWC across nations. While SRWC is considered to be forest in some countries, it is treated as an agricultural crop in other nations, making comparisons and predictions across borders difficult.

From society-nature interaction to bioenergy: the Japanese example of Satoyama

During my time as a PhD student, I had the opportunity of visiting a number of places around the world, learning different approaches to and specific situations of forestry. One such example comes from Japan where Satoyama forests have a long tradition. Directly translated "sato" means "village" and "yama" "mountain" (Morimoto, 2011). The translation points at the conceptual meaning of Satoyama, which describes the typical landscape between villages and mountains (Okuyama). Although there are many definitions, one probably finds a suitable one in the Daijirin dictionary: "the woods close to the village which was a source of such resources as fuel-wood and edible wild plants, and with which people traditionally had a high level of interaction" (Matsumura 2002, translated by Knight, 2010). Satoyama could be understood as an integrative approach of landscape management, including the provision of raw materials such as wood, natural fertilizer (see the transfer from nutrients from forests to agricultural systems as previously mentioned), drinking water and recreation opportunities. Besides its inherent economic and ecological values, it provides a sphere for human-nature interactions and as such, it opens a window to see how Japanese perceive and value their natural environment over time (Knight, 2010). As a consequence of small-scale structures and specific management, Satoyama woodlands represent hotspots of biodiversity (Morimoto, 2011). They are pegged into a landscape of paddy fields, streams and villages. From a silvicultural point of view, Satoyama woodlands consist of mainly deciduous species, such as *Quercus acutissima* and *Quercus serrata* (however, Japanese cedar is sometimes used to delimit parcels of different ownership) which are coppiced on rotational cycles of 15-20 years, creating a mosaic of age classes (Terada et al., 2010). Along with its scenic beauty and recreational capabilities, which is doubtlessly a strong asset close to urban megacities, Satoyama woodlands are capable of providing goods and services for generations; even under conditions of changing demands and specific needs of generations (Yokohari and Bolthouse, 2011).

Coppice is a traditional forest management system in a number of countries and can be found in Eastern Austria (Bruckman et al., 2011). In contrast to Satoyama, coppice forests in Austria were traditionally managed to obtain fuel-wood and because of suitable environmental conditions for coppicing. Low levels of precipitation (~500 mm yr^{-1}) promote coppicing since a fully established root system is present at any time, stimulating re-sprouting even under periods of drought. However, the holistic approach of landscape management is by far not considered to the same extent as it is for Satoyama.

The importance of coppice forests for biomass provision ceased with the utilization of fossil fuels. Likewise, Satoyama was devaluated as a result of the "fuel revolution" in Japan (Yokohari and Bolthouse, 2011), and large areas were discarded, leading to abandoned or poorly managed Satoyama woodlands. This is comparable to the divergent silvicultural structures with diffuse standards in Austria (Hochbichler, 1993).

Satoyama woodlands are now back in the public interest, starting in the 1980s, where volunteer groups have formed, being part of the Satoyama movement which urged for development of adequate environmental policies (Terada et al., 2010). Although most groups are focussed on recreational activities in urban and peri-urban areas, the potential of Satoyama to provide biomass for energetic utilization has recently gained attention. Terada et al. (2010) calculated a C reduction potential of 1.77 t ha^{-1} yr^{-1} of C for the Satoyama woodlands if coppiced and the biomass is utilized in CHP power plants. Considering the total study area (including settlements, agricultural areas and infrastructure, the C reduction potential is still 0.24 t ha^{-1} yr^{-1}. However, practices such as cyclic litter removal have to be evaluated in regard of the base cation removal rates and subsequent acidification, which ultimately leads to lower ecosystem productivity.

The Fukushima Daiichi nuclear incident clearly showed the threat of nuclear fission energy sources. In combination with efforts to cut carbon emissions, paired with rising demands for energy, the situation caused a shift towards sustainable, clean and safe forms of energy provision. Satoyama perfectly fulfils these requirements and might be able to be part of the future energy system while being neutral in terms of GHG release.

It was shown that Satoyama woodlands are capable of conserving traditional forest management systems, manifesting a strong link between society and nature, as well as providing answers towards global challenges. Satoyama might represent a good model for sustainable resource management that the rest of the world can learn from (Knight, 2010; Morimoto, 2011). A study to evaluate Satoyama landscapes on a global basis was started under the "Satoyama initiative", launched by the Japanese Ministry of the Environment.[2]

Pyrolysed biomass – a revival of ancient knowledge

Tropical forest ecosystems are characterized by poor and heavily weathered soils and yet they are a hotspot of biodiversity and play an important role in global climate regulation as previously mentioned. Organic matter is recycled rapidly and soils mainly consist of kaolinites as the dominating clay mineral, offering relatively inefficient exchange sites for base cations. The result is the lowest cation exchange capacity (CEC) among clay minerals (Brady and Weil, 2001) which is another factor for low rates of nutrient retention. Occasionally, small patches of highly fertile soils, suitable for sustainable agriculture, are found in South America. They are known as Anthropogenic Dark Earths or "terra preta de Índio" (terra preta) (Glaser and Birk, 2012). Amendment of various forms of organic matter and specifically, biochar, led to the formation of this rather untypical soil. Biochar is identical to charcoal, which is produced by pyrolysis (thermochemical decomposition without the presence of oxygen) of biomass. In the case of soil amendment, it is called biochar instead of charcoal. Biochar is a key component of terra preta and it was recently rediscovered as a potential candidate of negative CO_2 emissions. Biochar has turned out to be extremely resilient against chemical decomposition, even under tropical conditions as recently reported (Schneider et al., 2011). Based on a chronosequence approach covering a time-span of 100 years, they studied molecule markers of pyrogenic C, concluding that they did not change as well as the total biochar stocks. This could explain why fertile terra preta could still be found today, although they were formed by pre-Columbian inhabitants, as confirmed by radiocarbon dating and archaeological evidence (Glaser and Birk, 2012). Another recent study points at the mechanisms of stabilizing biochar. Organo-mineral interactions, especially with clay minerals, might explain the extreme resilience of biochar in soils which was to a greater extent associated with the heavy fraction (Vasilyeva et al., 2011). In accordance with the previously mentioned study, they did not observe significant changes in both quality and quantity of pyrogenic carbon (PyC = Biochar) within a time span covering 55 years from a long-term experiment which was established in 1935. Based on a recent meta-analysis of 177 studies Jeffery et al. (2011) suggest that biochar amendment improved soil chemical and physical properties overall, where the improvement in terms of crop productivity was stronger in soils with low to neutral pH values and soils with a coarse to medium texture. This might indicate the two main reasons for increased crop productivity, which are the liming effect and improving water holding capacity, along with improved nutrient availability; according to the authors. Accordingly, Laird et al. (2010) reports a greater water retention, larger specific surface areas, higher CEC, and higher pH values relative to unamended controls in their soil-column incubation experiment. A three year field experiment demonstrates that aboveground biomass of an agricultural crop as well as foliar N contents increased. Increased soil respiration, fungal and bacterial growth as well as turnover were reported to occur belowground (Jones et al., 2012). This ultimately leads to the question if biochar amendment causes a priming effect and there will be higher CO_2 emissions from the soil as a consequence of elevated respiration. Especially labile fractions of organic C, incorporated by root turnover, exudates and litter fall are prone to be respired under such conditions. And indeed, it was shown that a priming effect exists with significant losses of CO_2-C following biochar incorporation (Luo et al., 2011). However, according to the authors, the loss is compensated for by far with the actual biochar amendment and the loss is much smaller than if non-pyrolysed biomass were incorporated.

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2 See http://satoyama-initiative.org/en/ for more details.

In terms of soil microbiology, a comprehensive review by Lehmann et al. (2011) points out that microbial biomass has been found to increase in most studies after biochar amendment and the initial biochar pH value (which could be acid or alkaline) has a great influence on total microbial abundance. They also observed a significant change in microbial community composition and enzyme activities and suggest this is a result of biogeochemical effects of biochar on element cycles, plant pathogens and crop growth. The chemical composition of biochar, which is determined by the type of biomass which is used for pyrolysis and specific settings during the process of pyrolysis (temperature, duration, oxygen content etc.), has a great influence on the result of biochar amendment on a specific soil. Therefore, it is suggested to vary the chemical composition of the biochar and the condensation grade in order to stabilize biochars and other nutrients could be introduced to the biochar structure (Steinbeiss et al., 2009). This would then result in optimal fertilization and improvement of soil properties, tuned for local requirements.

So far, there is quite some evidence that biochar enhances soil properties, especially in the case of poor and heavily weathered soils. It was also shown that the positive effects of biochar amendment are long-term because of the inherent resilience of biochar, based on organo-mineral interactions. Research activities on biochar have recently increased based on the fact that biochar amendment has the potential to realize negative C emissions based on the resilience of biochar in the soil. Biogas (syngas) and bio-oil are co-produced during pyrolysis along with charcoal, depending on the feedstock and process parameters. These can substitute fossil sources of crude oil and natural gas, hence reducing fossil C emissions. Woolf et al. (2010) quantified the maximum sustainable technical potential of biochar to mitigate climate change. They came up with an estimation of 1.8 Pg of CO_2 C equivalents (C_e) annually, which represents 18% of current global CO_2 emissions (see figure 3) or 12% of current CO_2 C_e emissions. A range of different feed stocks were considered, but sustainability criteria were applied to prevent negative ecosystem and social impacts (e.g. from land use change, soil erosion, contamination by industrial waste, competition with food production etc.). However, their estimates are based on current availability of biomass and demographic developments (population growth) are not considered. Likewise, impacts of climate change on feedstock availability, which is likely to happen as a consequence of droughts and other extreme weather events, are not reflected. Nevertheless, biochar amendment seems to have great potential in mitigating climate change while improving soil conditions. A topic for further studies is to determine if biochar amendment in forest soils, similar to liming, might be an option to compensate for nutrient losses (enhancing soil properties) after harvesting biomass for pyrolysis.

An integrative approach was recently initiated by the author in the framework of a KORANET project[3], aiming at assessing the potential of biomass pyrolysis on climate change mitigation and energy provision on national levels. Proposed is a consortium of three nations, South Korea, Turkey and Austria (project coordination). The proposal follows a cascade approach as shown in figure 7. The project was selected for funding in July, 2012.

Concluding Remarks

Specific types of biomass, i.e. wood and wood-derived fuels, have a long history of being the major source of thermal energy since humanity learned to control fire which was a turning point in human development. These sources have not lost their significance in many developing countries, especially in domestic settings. However, over-population, climatic conditions and low efficiency cause shortages of fuel-wood in many regions, e.g. Ethiopia or Northern India. This would not be the major problem in developed nations, where

3 The Korean scientific cooperation network with the European Research Area (KORANET) aims at intensifying Science and Technology cooperation between Korea and Europe. It is funded under FP7 (Project number: FP7-226154) and the current proposal was submitted to the 2012 KORANET Joint Call on Green Technologies and selected for funding.

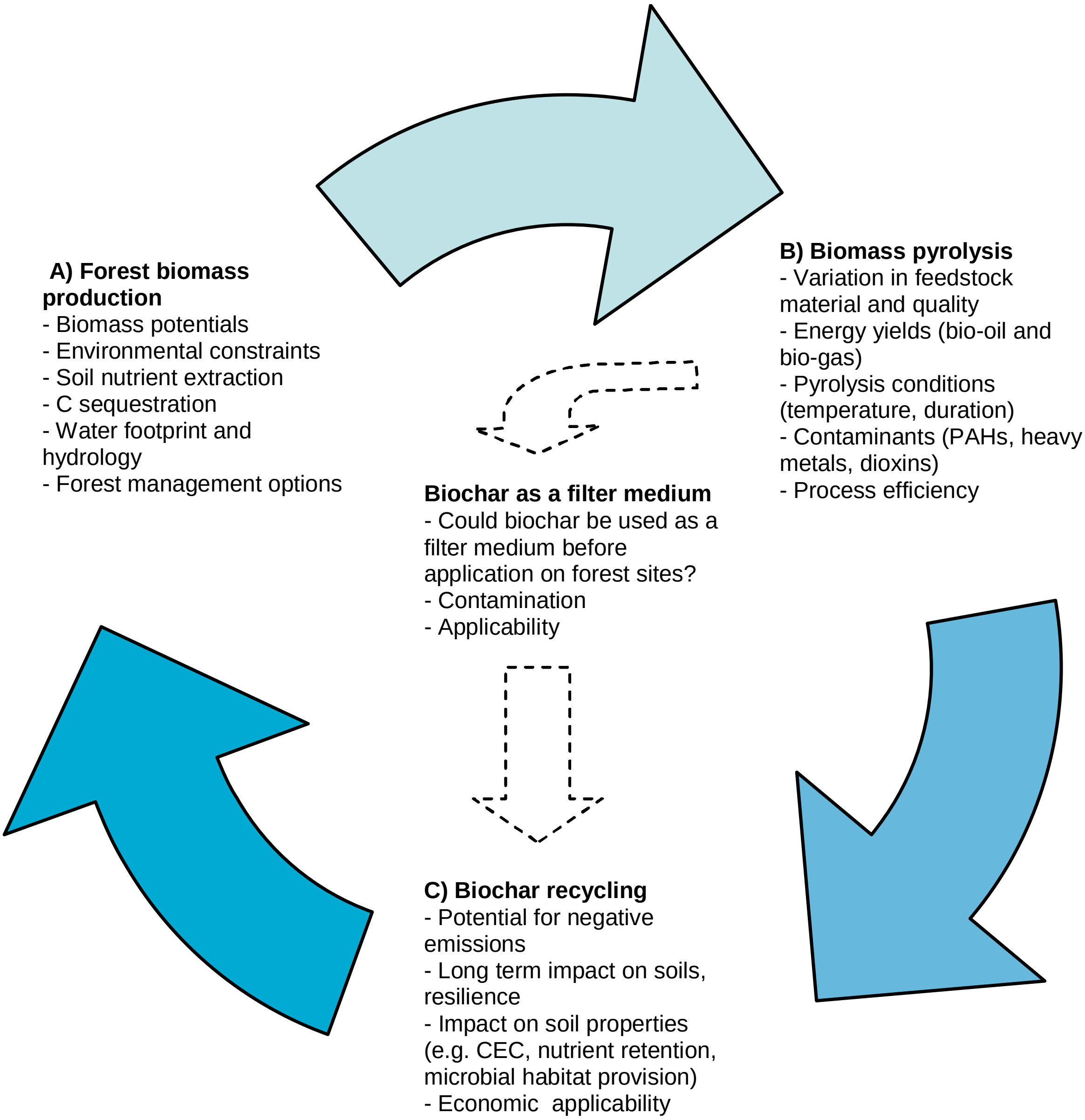

Figure 7: A multi-cascade recycling approach of sustainable biochar amendment as proposed in a KORANET Project. A specific question will deal with potential biochar utilization as an activated carbon filter medium prior to soil amendment.

biomass as a source for thermal energy and raw materials for industrial processes has recently gained increased attention as a renewable and greenhouse-friendly commodity. Hence, sustainable management is required to prevent adverse consequences for society and the environment. Paradoxically biomass is tagged to be sustainable per se, although this is by no means substantiated since it depends on the local conditions and the management used. Thus a critical life cycle analysis is needed to assess the benefits in comparison to other energy sources. Compared to conventional fossil sources of energy where "sustainability" is only directed at a wise and efficient use of a finite resource, sustainability of biomass from forests has to be considered in a much wider context. Biomass represents one of a multitude of ecosystem services which depends on the given ecosystem. As a matter of fact, ecosystems are extremely heterogeneous from global to forest stand scale, mainly controlled by environmental conditions, such as climate, soils and resulting species composition and anthropogenic impacts. Likewise, society's demands for specific ecosystem services are highly diverse. While recreation and provision of a clean environment (water, air) might be the most important service close to urban areas and settlements, the provision of wood and by-products as economic commodities might be important in more remote, but accessible regions. This also implies one of the major differences to the current energy system. Besides the fact that bio-energy alone is not capable of providing the same amount of sustainable energy we are currently receiving from fossil fuels, the infrastructure has to be decentralized, directed at local demands and supplies. Both the economic stability as well as the benefits for environment and society can be marginal or even negative in the case of large scale bioenergy power plants.

Based on a global review, Lattimore et al. (2009) identified six main areas of environmental constraints in regard to wood-fuel production:

1. Soils
2. Hydrology and water quality
3. Site productivity
4. Forest biodiversity
5. Greenhouse gas balances
6. Global and supply-chain impacts of bioenergy production

This listing elucidates the challenge of applying sustainability criteria to biomass production, since a large set of criteria and indicators for bioenergy production systems has to be implied. As a consequence, sustainability comes at the cost of a high complexity of ensuring mechanisms. Nonetheless, a set of regionally adaptable principles, criteria, indicators and verifiers of sustainable forest management, as suggested by Lattimore et al. (2009) might be inevitable to ensure best practices according to the current status of scientific knowledge. They propose an adaptive forest management framework with continuous monitoring in certification systems to ensure efficacy and continual improvement.

Policy has to ensure that such regulations are implemented in binding regulations. Corruption and greed for short-term profit maximization are still major problems, providing a base for unsustainable use of resources, especially in countries with unstable political situations.

Apart from the aforementioned challenges there are a number of examples, highlighting the potential of biomass as a source of sustainable energy. The satoyama woodlands in Japan are an example for traditional sustainable woodland management, carefully balancing ecosystem services in regions with relatively high population density, thus implying a high level of social-nature interaction. Since this form of landscape management proved to be successful over centuries with a high degree of flexibility in regard to changing demands over time, it might be a model of sustainable land use for other regions in the world. Biochar is another example of knowledge that is not new, but has a potential to help mitigate climate change and contribute to a sustainable energy future. Up to 18% of the current (2010) global annual emissions of CO_2 can be neutralized, largely by C sequestration in soils (Woolf et al. 2010). A sustainable future, entirely based on renewable sources of energy without harming our environment is possible. Certainly it will be based on decentralized structures with a large pool of different sources of renewable energy, a situation with another great advantage of having a high level of resilience in comparison to our current system. Biomass will play a role in areas with sufficient supplies. However, changing lifestyles (reduced energy consumption, less meat in diets, higher efficiency), especially in the developed regions of the world may be a very important step to be started immediately.

Relevance and impact of the publications

Paper 1: Carbon pools and temporal dynamics along a rotation period in *Quercus* dominated high forest and coppice with standards stands

Paper 1 focuses on organic C pools and their dynamic properties under two common forest management systems (high forest and coppice with standards) in Austria. Both aboveground and belowground pools are considered to obtain total ecosystem pools of different compartments. A carbon inventory, as implemented in our study, is a first step to evaluate ecosystem C dynamics and an inevitable step in assessing biomass potentials. We hypothesized that forest management influences ecosystem C pools and dynamics and found that aboveground pools are highly affected by silvicultural interventions, while belowground pools are relatively stable and react slowly. However, the share between above- and belowground pools remains constant across our study region, which indicates strong climatic drivers controlling belowground C accumulation. Soils play an important role and the quantity as well as the quality of soil C pools is mainly determined by soil type and species composition. Besides litterfall, root and mycorrhizal turnover represents an important, eventually the largest, flux of atmospheric C to the soil, where it can be considered as successful sequestration if it becomes part of the recalcitrant fraction. At this point, a conceptual dilemma ultimately emerges: While low microbial activities and a high rate of C sequestration are favourable in terms of high soil C stocks, biomass production relies on fast C turnover and mineralization, contradicting aims of sequestration; which becomes evident especially in agricultural systems. We were able to show the differences in belowground fine root masses and their dynamic aspect in the different forest management systems, in combination with dynamic changes of the root/shoot ratio.

Nitrogen plays a key role in the organic C cycle as previously mentioned. Based on C:N ratios, we were able to demonstrate reduced competition for mineralized N in the older stands of high forest, resulting in narrower ratios in topsoil horizons and increased heterotrophic respiration. Foliar N:P ratios suggest moderate N limitation in the youngest high forest stand (11 years) as revealed by a follow-up investigation. Since N pools are considerably high, we expect that N availability might be lower due to competition with herbaceous ground vegetation and elevated microbial activity as the stand can be considered relatively open. Soil moisture was found to be low in combination with a high content of coarse material (gravel and sand) which might be another factor for limited N availability. We suggest forest management based on mixed broadleaved species and admixture of N-fixing species (e.g. *Acacia*) which are tolerant to drought on sites with high coarse material contents. It is expected that annual precipitation decreases and mean temperatures are rising in our study area as a consequence of climate change (Strauss et al., 2010). As a consequence, coppice management may perhaps be re-introduced in the high forest system if the management aim switches to biomass production for energetic utilization. Coppice has a fully functional root system at all times and facilitates re-sprouting even under dry conditions. Biomass harvests during the vegetative period should be avoided in order to minimize excessive nutrient extractions. The SOC and O-layer C pools are relatively low (especially O-layer C in the coppice chronosequence in our study) suggesting high C turnover rates. Hence, the potential for additional C sequestration is low and we assume that fine root turnover represents a more effective pathway for C sequestration in the soil at our particular sites.

Our results provide a basis for further research in stand development patterns as well as in the significance of soil types on C sequestration and biomass potentials. A follow-up study on the nutritional status (both below- and aboveground) is underway and some preliminary results were presented (see "Selected contributions at international scientific events"). In addition, our results may be used in modelling approaches (e.g. Roth C) in order to describe carbon budgets and fluxes at our sites. Our publication provides a good foundation for cooperation in regard to modelling as the author was contacted by a colleague from the EuroMediterranean Center for Climate Changes (CMCC) Division of Climate Change Impacts on agriculture, forests and natural ecosystems (IAFENT), Italy. Initiating talks on cooperation and integration of our

results into an existing model are anticipated for September 2012. Based on our results and previous work at these permanent *Quercus* plots, it would be interesting to study the role of mycorrhiza in the C cycle. Ingrowth meshbag approaches are a relatively new and promising method to describe the mycorrhizal communities and their potential influence on the site C metabolism and its dynamic change with stand development.
Moreover we were able to clearly show the potentials and limitations of the chronosequence approach which substitutes time for space. While we were able to describe changes in biomass C pools, we were unable to describe SOC pools although sampling sites were carefully selected.

Paper 2: Improved soil carbonate determination by FT-IR and X-ray analysis

Paper 2 represents an analytical approach to detect inorganic C in soils. The idea of this publication was born during the lab-work for paper 1. In carbonate-free soils, the total amount of C (C_t) represents SOC, which is the direct result of dry combustion analysis. However, soils in our study region consist of a wide range of parent materials with considerable amounts of calcite, originating from loess from the Northern Limestone Alps. Loess is an aeolian deposit which is of great regional importance because of the development of very fertile soils and consequent development of wine culture in this region. A part of the study region which was the basis for paper 2 was additionally influenced by the Danube River, causing a variety of coarse material deposits containing carbonates. In order to estimate SOC contents, typically total organic C contents are measured and inorganic C (carbonates) is subtracted from C_t to resolve SOC. SIC and SOC are in tight relation as dissolved organic matter (DOM) controls accumulation and dissolution particularly of calcite (Sartori et al., 2007). As a result, SIC is typically being translocated to deeper soil horizons after afforestation (Chang et al., 2012). On the other hand, high exchangeable Ca^{2+} may have slower organic C decomposition as a consequence of immediate bonding of any free OM with Ca^{2+} ions (Clough and Skjemstad, 2000). The stabilization effect is also reported after addition of calcite to soil samples in a lab experiment. The efficiency of extracting humic acids by NaOH was reduced as a consequence of a bridging effect of Ca between humic acids (HA) and clay as well as crosslinking of functional groups resulting in smaller, denser and more rigid molecules which are more stable (Muneer and Oades, 1989). Consequently, SIC is an important and reactive compartment which influences the SOC pool and C sequestration, both direct and indirect (via SOC). It should be therefore considered more frequently in studies addressing soil C dynamics and processes as it was done in the past. Paper 2 proposes a new approach of accurately determining carbonate, while being able to distinguish between calcite and dolomite.
The pH value may be used as a proxy for carbonate occurrence to keep the necessary sample amount low. All samples with a pH value larger than a certain threshold value (pH[$CaCl_2$] > 6 for the current study) undergo the procedure of inorganic C determination. Gas-volumetric methods are common, such as Scheibler (ON L 1084-99, 1999) but the analytical precision is relatively weak and the reaction times vary greatly depending on the type of carbonate.
In our study region, carbonate occurs as calcite ($CaCO_3$) and/or dolomite ($CaMg[CO_3]_2$), in different proportions, depending on the parent material and biological processes. In samples with high calcite relative to dolomite contents, biological formation of secondary carbonates (calcite) can be assumed. While the Scheibler reaction is relatively fast in the case of calcite samples, it might take up to several minutes if dolomite is present, with significant idle times in between. This could consequently result in an underestimation of inorganic C and ultimately overestimation of SOC.
Spectroscopic approaches have proved their potential in inorganic C determination (Janik and Skjemstad, 1995; Tatzber et al., 2007; Ji et al., 2009; Tatzber et al., 2011). However, none of the methods differentiated between calcite and dolomite. Hence we suggest determining the calcite/dolomite ratio using X-ray Diffraction and use the spectral information in combination with Fourier Transform Mid-Infrared Spectroscopy as recommended by Ji et al. (2009) for increased model prediction accuracy of inorganic C. Since our

plots were set up as long term monitoring sites, it is feasible to use models to predict inorganic C contents on similar substrates. Our model is based on partial least squares regression (PLS or PLSR). PLS is among the most commonly used regressions for estimation of parameters based on a great number of observations, e.g. spectral chemometrics (Rossel et al., 2006). Hence the first step is a reduction of dimensions prior to the actual regression which is then derived from scores of principal components. The method is very robust in terms of missing data and noise and multicollinearity among the independent input values can be handled. It was recently confirmed that this method offers a good predictive ability for our dataset, based on an assessment of different regression techniques (stepwise regression, robust regression with feature selection, lasso regression, ridge regression, elastic net, principal component regression and PLS) (Schwanghart et al., 2012). Results of the assessment suggested that PLS, although being one of the simplest approaches, performed very well in predicting SOC from spectra of different environments (Schwanghart, 2012, pers.comm.). Our model shows best performance if X-ray diffraction data are included and calcite-dolomite ratios are considered at the gas-volumetric Scheibler estimation for the model calibration and validation, in contrast to Fourier Transform Mid-Infrared data only. Hence our model offers a possibility to precisely estimate inorganic C in our study region. This may be helpful in determining soil organic carbon pools under the condition of similar soil properties. However, this approach can be used on any calcareous soil provided a suitable dataset is available for model parameterization and validation. In the context of bioenergy provision it might be helpful to monitor belowground SIC dynamics as many energy crops are being set up in arid regions, with considerable amounts of carbonate (e.g. Sartori et al., 2007).

References

Aichele, R., Felbermayr, G., 2012. Kyoto and the carbon footprint of nations. Journal of Environmental Economics and Management 63, 336-354.

AlFarra, H.J., Abu-Hijleh, B., 2012. The potential role of nuclear energy in mitigating CO_2 emissions in the United Arab Emirates. Energy Policy 42, 272-285.

Aronsson, P.G., Bergstrom, L.F., Elowson, S.N.E., 2000. Long-term influence of intensively cultured short-rotation Willow Coppice on nitrogen concentrations in groundwater. Journal of Environmental Management 58, 135-145.

Bodas Freitas, I.M., Dantas, E., Iizuka, M., 2012. The Kyoto mechanisms and the diffusion of renewable energy technologies in the BRICS. Energy Policy 42, 118-128.

Brady, N.C., Weil, R.R., 2001. The nature and properties of soils. Prentice Hall, Upper Saddle River, NJ.

Bruckman, V.J., Yan, S., Hochbichler, E., Glatzel, G., 2011. Carbon pools and temporal dynamics along a rotation period in *Quercus* dominated high forest and coppice with standards stands. Forest Ecology and Management 262, 1853-1862.

Canadell, J.G., Le Quéré, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., Gillett, N.P., Houghton, R.A., Marland, G., 2007. Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proceedings of the National Academy of Sciences of the USA 104, 18866-18870.

Chang, R., Fu, B., Liu, G., Wang, S., Yao, X., 2012. The effects of afforestation on soil organic and inorganic carbon: A case study of the Loess Plateau of China. Catena 95, 145-152.

Clough, A., Skjemstad, J.O., 2000. Physical and chemical protection of soil organic carbon in three agricultural soils with different contents of calcium carbonate. Soil Research 38, 1005-1016.

Cranston, G.R., Hammond, G.P., 2012. Carbon footprints in a bipolar, climate-constrained world. Ecological Indicators 16, 91-99.

Cuney, M., 2009. The extreme diversity of uranium deposits. Mineralium Deposita 44, 3-9.

De Vries, W., Reinds, G.J., Gundersen, P., Sterba, H., 2006. The impact of nitrogen deposition on carbon sequestration in European forests and forest soils. Global Change Biology 12, 1151-1173.

Dickmann, D.I., 2006. Silviculture and biology of short-rotation woody crops in temperate regions: Then and now. Biomass & Bioenergy 30, 696-705.

Diochon, A., Kellman, L., Beltrami, H., 2009. Looking deeper: An investigation of soil carbon losses following harvesting from a managed northeastern red spruce (*Picea rubens* Sarg.) forest chronosequence. Forest Ecology and Management 257, 413-420.

Dixon, R.K., Solomon, A.M., Brown, S., Houghton, R.A., Trexier, M.C., Wisniewski, J., 1994. Carbon Pools and Flux of Global Forest Ecosystems. Science 263, 185-190.

Don, A., Bärwolff, M., Kalbitz, K., Andruschkewitsch, R., Jungkunst, H.F., Schulze, E.-D., 2012. No rapid soil carbon loss after a windthrow event in the High Tatra. Forest Ecology and Management 276, 239-246.

Eswaran, H., Reich, P., Kimble, J., 2000. Global carbon stocks. In: Lal, R., Kimble, J., Eswaran, H., Stewart, B. (Eds.), Global Climate Change and Pedogenic Carbonates. CRC Press, Boca Raton, pp. 15-25.

FAO, 2010. The State of Food Insecurity in the World – Addressing food insecurity in protracted crises. Food and Agriculture Organization of the United Nations, Rome.

Galli, A., Wiedmann, T., Ercin, E., Knoblauch, D., Ewing, B., Giljum, S., 2012. Integrating Ecological, Carbon and Water footprint into a "Footprint Family" of indicators: Definition and role in tracking human pressure on the planet. Ecological Indicators 16, 100-112.

Gärdenäs, A.I., Ågren, G.I., Bird, J.A., Clarholm, M., Hallin, S., Ineson, P., Kätterer, T., Knicker, H., Nilsson, S.I., Näsholm, T., Ogle, S., Paustian, K., Persson, T., Stendahl, J., 2011. Knowledge gaps in soil carbon and nitrogen interactions – From molecular to global scale. Soil Biology and Biochemistry 43, 702-717.

Garten, J., C.T., Wullschleger, S.D., Classen, A.T., 2011. Review and model-based analysis of factors influencing soil carbon sequestration under hybrid poplar. Biomass & Bioenergy 35, 214-226.

Gedalof, Z.e., Berg, A.A., 2010. Tree ring evidence for limited direct CO_2 fertilization of forests over the 20th century. Global Biogeochemical Cycles 24, GB3027.

Glaser, B., Birk, J.J., 2012. State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Índio). Geochimica et Cosmochimica Acta 82, 39-51.

Glatzel, G., 1991. The impact of historic land use and modern forestry on nutrient relations of Central European forest ecosystems. Nutrient Cycling Agroecosystems 27, 1-8.

Godbold, D., Hoosbeek, M., Lukac, M., Cotrufo, M., Janssens, I., Ceulemans, R., Polle, A., Velthorst, E., Scarascia-Mugnozza, G., De Angelis, P., Miglietta, F., Peressotti, A., 2006. Mycorrhizal Hyphal Turnover as a Dominant Process for Carbon Input into Soil Organic Matter. Plant and Soil 281, 15-24.

Grandy, A.S., Neff, J.C., 2008. Molecular C dynamics downstream: The biochemical decomposition sequence and its impact on soil organic matter structure and function. Science of the Total Environment 404, 297-307.

Grogan, P., Matthews, R., 2002. A modelling analysis of the potential for soil carbon sequestration under short rotation coppice willow bioenergy plantations. Soil Use and Management 18, 175-183.

Gupta, J., Olsthoorn, X., Rotenberg, E., 2003. The role of scientific uncertainty in compliance with the Kyoto Protocol to the Climate Change Convention. Environmental Science and Policy 6, 475-486.

Hamburg, S.P., 2000. Simple rules for measuring changes in ecosystem carbon in forestry-offset projects. Mitigation and Adaptation Strategies for Global Change 5, 25-37.

Heumesser, U., 2012. Biomassekraftwerk Simmering. Magistratsabteilung 20, Vienna. Available: http://www.wien.gv.at/stadtentwicklung/energieplanung/zahlen/erneuerbar/biomassekraftwerk.html. Last accessed: 01st June 2012.

Hochbichler, E., 1993. Methods of oak silviculture in Austria. Annals of Forest Science 50, 583-591.

Hochbichler, E., Bruckman, V.J., Spinka, S., Glatzel, G., Grieshofer, H., 2009. Untersuchungen zur Dynamik der Biomassen- und Kohlenstoffvorräte in Niederwäldern mit Überhälter, Mittel- und Hochwäldern. DaFNE Research Reports. University of Natural Resources and Life Sciences, Department for forest and soil sciences, Vienna, pp. 1-154.

Hubbert, M.K., 1949. Energy from fossil fuels. Science 109, 103-109.

Huenteler, J., Schmidt, T.S., Kanie, N., 2012. Japan's post-Fukushima challenge – implications from the German experience on renewable energy policy. Energy Policy, 6-11.

International Energy Agency, 2011a. CO_2 Emissions from Fuel Combustion – Highlights. IEA Statistics. OECD/IEA, Paris.

International Energy Agency, 2011b. World Energy Outlook 2011 – Executive Summary. OECD Publishing, Paris.

IPCC, 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva.

Jandl, R., 1991. Biogeochemical processes in deciduous forests of the Vienna Woods with *Allium ursinum* ground cover. Dissertation, Institute of Forest Ecology, Universität für Bodenkultur Wien, Vienna.

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K., Byrne, K.A., 2007. How strongly can forest management influence soil carbon sequestration? Geoderma 137, 253-268.

Janik, L.J., Skjemstad, J.O., 1995. Characterization and Analysis of Soils Using Mid-infrared Partial Least-Squares. II.* Correlations with Some Laboratory Data. Australian Journal of Soil Research 33, 637-650.

Jeffery, S., Verheijen, F.G.A., van der Velde, M., Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agriculture, Ecosystems & Environment 144, 175-187.

Jha, P., Prasad Mohapatra, K., 2010. Leaf litterfall, fine root production and turnover in four major tree species of the semi-arid region of India. Plant and Soil 326, 481-491.

Ji, J.F., Ge, Y., Balsam, W., Damuth, J.E., Chen, J., 2009. Rapid identification of dolomite using a Fourier Transform Infrared Spectrophotometer (FTIR): A fast method for identifying Heinrich events in IODP Site U1308. Marine Geology 258, 60-68.

Jobbágy, E.G., Jackson, R.B., 2000. THE VERTICAL DISTRIBUTION OF SOIL ORGANIC CARBON AND ITS RELATION TO CLIMATE AND VEGETATION. Ecological Applications 10, 423-436.

Jones, D.L., Rousk, J., Edwards-Jones, G., DeLuca, T.H., Murphy, D.V., 2012. Biochar-mediated changes in soil quality and plant growth in a three year field trial. Soil Biology and Biochemistry 45, 113-124.

Kiehl, J.T., Trenberth, K.E., 1997. Earth's Annual Global Mean Energy Budget. Bulletin of the American Meteorological Society 78, 197-208.

Knapp, V., Pevec, D., Matijević, M., 2010. The potential of fission nuclear power in resolving global climate change under the constraints of nuclear fuel resources and once-through fuel cycles. Energy Policy 38, 6793-6803.

Knicker, H., 2011. Soil organic N – An under-rated player for C sequestration in soils? Soil Biology and Biochemistry 43, 1118-1129.

Knight, C., 2010. The Discourse of "Encultured Nature" in Japan: The Concept of Satoyama and its Role in 21st-Century Nature Conservation. Asian Studies Review 34, 421-441.

Knohl, A., Schulze, E.D., Kolle, O., Buchmann, N., 2003. Large carbon uptake by an unmanaged 250-year-old deciduous forest in Central Germany. Agricultural and Forest Meteorology 118, 151-167.

Kok, K.D., 2009. Nuclear engineering handbook. CRC Press, Boca Raton.

Kongoi, Z., Bonten, L., de Vries, W., 2012. Impacts of changes in climate, nitrogen deposition, ozone and CO_2 exposure on forest carbon sequestration: a meta-analysis. In: Augustaitis, A., Bytnerowicz, A., Paoletti, E. (Eds.), Biological Reactions of Forests to Climate Change and Air Pollution. IUFRO RG 7.01.00, Kaunas, Lithuania.

Kubiszewski, I., Cleveland, C.J., Endres, P.K., 2010. Meta-analysis of net energy return for wind power systems. Renewable Energy 35, 218-225.

Laird, D.A., Fleming, P., Davis, D.D., Horton, R., Wang, B., Karlen, D.L., 2010. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma 158, 443-449.

Lal, R., 2005. Forest soils and carbon sequestration. Forest Ecology and Management 220, 242-258.

Lal, R., 2008. Carbon sequestration. Philosophical Transactions of the Royal Society B: Biological Sciences 363, 815-830.

Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences of the USA 108, 3465-3472.

Lattimore, B., Smith, C.T., Titus, B.D., Stupak, I., Egnell, G., 2009. Environmental factors in woodfuel production: Opportunities, risks, and criteria and indicators for sustainable practices. Biomass and Bioenergy 33, 1321-1342.

Le Quere, C., Raupach, M.R., Canadell, J.G., Marland, G., et al., 2009. Trends in the sources and sinks of carbon dioxide. Nature Geoscience 2, 831-836.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D., 2011. Biochar effects on soil biota – A review. Soil Biology & Biochemistry 43, 1812-1836.

Lu, C., Tian, H., Liu, M., Ren, W., Xu, X., Chen, G., Zhang, C., 2011. Effect of nitrogen deposition on China's terrestrial carbon uptake in the context of multifactor environmental changes. Ecological Applications 22, 53-75.

Luo, Y., Durenkamp, M., De Nobili, M., Lin, Q., Brookes, P.C., 2011. Short term soil priming effects and the mineralisation of biochar following its incorporation to soils of different pH. Soil Biology and Biochemistry 43, 2304-2314.

Lutz, W., Sanderson, W., Scherbov, S., 2001. The end of world population growth. Nature 412, 543-545.

Luyssaert, S., Schulze, E.D., Borner, A., Knohl, A., Hessenmoller, D., Law, B.E., Ciais, P., Grace, J., 2008. Old-growth forests as global carbon sinks. Nature 455, 213-215.

Ma, X.Q., Heal, K.V., Liu, A.Q., Jarvis, P.G., 2007. Nutrient cycling and distribution in different-aged plantations of Chinese fir in southern China. Forest Ecology and Management 243, 61-74.

Mann, M., Amman, C., Bradley, R., Briffa, K., Jones, P., Osborn, T., Crowley, T., Hughes, M., Oppenheimer, M., Overpeck, J., Rutherford, S., Trenberth, K., Wigley, T., 2003. On past temperatures and anomalous late-20th-century warmth. Eos Transactions AGU 84, 256-258.

Mann, M.E., Bradley, R.S., Hughes, M.K., 1998. Global-scale temperature patterns and climate forcing over the past six centuries. Nature 392, 779-787.

Mann, M.E., Zhang, Z., Hughes, M.K., Bradley, R.S., Miller, S.K., Rutherford, S., Ni, F., 2008. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. Proceedings of the National Academy of Sciences of the USA 105, 13252-13257.

Matthews, R., Grogan, P., 2001. Potential C-sequestration rates under short-rotation coppiced willow and Miscanthus biomass crops: a modelling study. Aspects of Applied Biology 65, 303-312.

McHenry, H.M., 2009. Human Evolution. In: Ruse, M., Travis, J. (Eds.), Evolution: The First Four Billion Years. The Belknap Press of Harvard University Press, Cambridge, Massachusetts, p. 265.

Melero, J.A., Iglesias, J., Garcia, A., 2012. Biomass as renewable feedstock in standard refinery units. Feasibility, opportunities and challenges. Energy & Environmental Science 5, 7393-7420.

Moore, D., Cranston, G., Reed, A., Galli, A., 2012. Projecting future human demand on the Earth's regenerative capacity. Ecological Indicators 16, 3-10.

Morimoto, Y., 2011. What is Satoyama? Points for discussion on its future direction. Landscape and Ecological Engineering 7, 163-171.

Munday, P.L., Dixson, D.L., McCormick, M.I., Meekan, M., Ferrari, M.C.O., Chivers, D.P., 2010. Replenishment of fish populations is threatened by ocean acidification. Proceedings of the National Academy of Sciences of the USA 107, 12930-12934.

Muneer, M., Oades, J.M., 1989. The Role of Ca-Organic Interactions in Soil Aggregate Stability. III. Mechanisms and Models. Australian Journal of Soil Research 27, 411-423.

Nabuurs, G.J., Thurig, E., Heidema, N., Armolaitis, K., Biber, P., Cienciala, E., Kaufmann, E., Makipaa, R., Nilsen, P., Petritsch, R., Pristova, T., Rock, J., Schelhaas, M.J., Sievanen, R., Somogyi, Z., Vallet, P., 2008. Hotspots of the European forests carbon cycle. Forest Ecology and Management 256, 194-200.

Neftel, A., Moor, E., Oeschger, H., Stauffer, B., 1985. Evidence from polar ice cores for the increase in atmospheric CO_2 in the past two centuries. Nature 315, 45-47.

ÖN L 1084-99, 1999. Chemical analyses of soils – Determination of carbonate. Austrian Standards Institute (Ed.), ÖNORM L 1084. Austrian Standards Institute, Vienna.

Österreichische Bundesforste AG, 2005. Neue Allianz der Forstwirtschaft für Biomasse. Austrian Federal Forests. Available: http://www.oebf.at/index.php?id=54&tx_ttnews%5Btt_news%5D=71&cHash=015ae5bbe61324ab7f433c60c3e2fd6e. Last accessed 27th Aug 2012.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A Large and Persistent Carbon Sink in the World's Forests. Science 333, 988-993.

Peters, G., Marland, G., Le Quéré, C., Boden, T., Canadell, P., Raupach, M., 2012. An update of the global carbon budget: Emissions rebound after the Global Financial Crisis (GFC). Conference contribution, Planet under Pressure 2012, London, UK, 26-29. March, 2012.

Pimentel, D., Pimentel, M., 2006. Global environmental resources versus world population growth. Ecological Economics 59, 195-198.

Plass, G.N., 1956. The Carbon Dioxide Theory of Climatic Change. Tellus 8, 140-154.

Poeplau, C., Don, A., 2012. Vulnerability of SOC stocks and fractions to different land-use change types in Europe (EGU2012-4239-1). European Geosciences Union General Assembly 2012. Geophysical Research Abstracts 14, Vienna.

Prentice, I.C., 2001. The Carbon Cycle and Atmospheric Carbon Dioxide. Climate Change 2001: The Scientific Basis IPCC. Cambridge University Press, Cambridge, UK, p. 192.

Rabbinge, R., 2007. Food security, food safety and sustainable development – Food, feed or fuel? Conference contribution, Vom Waldessen und Waldbrennen, Austrian Academy of Sciences, Vienna, 24.10.2007.

Rasse, D., Rumpel, C., Dignac, M.-F., 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant and Soil 269, 341-356.

Raupach, M.R., Canadell, J.G., 2010. Carbon and the Anthropocene. Current Opinion in Environmental Sustainability 2, 210-218.

Rechnungshof, 2007. WIEN ENERGIE – Bundesforste Biomasse Kraftwerk GmbH. Bericht des Rechnungshofes, Bund 2007/4. Austrian Audit Court, Vienna, pp. 241-257.

Richter, D.D., Markewitz, D., Trumbore, S.E., Wells, C.G., 1999. Rapid accumulation and turnover of soil carbon in a re-establishing forest. Nature 400, 56-58.

Rosén, K., Aronson, J.-A., Eriksson, H.M., 1996. Effects of clear-cutting on streamwater quality in forest catchments in central Sweden. Forest Ecology and Management 83, 237-244.

Rossel, R.A.V., Walvoort, D.J.J., McBratney, A.B., Janik, L.J., Skjemstad, J.O., 2006. Visible, near infrared, mid infrared or combined diffuse reflectance spectroscopy for simultaneous assessment of various soil properties. Geoderma 131, 59-75.

Rumpel, C., Kogel-Knabner, I., Bruhn, F., 2002. Vertical distribution, age, and chemical composition of organic carbon in two forest soils of different pedogenesis. Organic Geochemistry 33, 1131-1142.

Sartori, F., Lal, R., Ebinger, M.H., Eaton, J.A., 2007. Changes in soil carbon and nutrient pools along a chronosequence of poplar plantations in the Columbia Plateau, Oregon, USA. Agriculture, Ecosystems & Environment 122, 325-339.

Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M., Kogel-Knabner, I., Lehmann, J., Manning, D.A.C., Nannipieri, P., Rasse, D.P., Weiner, S., Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem property. Nature 478, 49-56.

Schneider, M.P.W., Lehmann, J., Schmidt, M.W.I., 2011. Charcoal quality does not change over a century in a tropical agro-ecosystem. Soil Biology and Biochemistry 43, 1992-1994.

Schulp, C.J.E., Nabulars, G.J., Verburg, P.H., de Waal, R.W., 2008. Effect of tree species on carbon stocks in forest floor and mineral soil and implications for soil carbon inventories. Forest Ecology and Management 256, 482-490.

Schulze, E.-D., Wirth, C., Heimann, M., 2000. Managing Forests After Kyoto. Science 289, 2058-2059.

Schuur, E.A.G., Abbott, B., 2011. Climate change: High risk of permafrost thaw. Nature 480, 32-33.

Schwanghart, W., Jarmer, T., Bayer, A., Hoffmann, U., Hunziker, M., Kuhn, N.J., Ehlers, M., 2012. Regression techniques for estimating soil organic carbon contents from VIS/NIR reflectance spectra (EGU2012-2328). Conference contribution, European Geosciences Union General Assembly 2012. Geophysical Research Abstracts 14, Vienna.

Seidl, R., Rammer, W., Jager, D., Currie, W.S., Lexer, M.J., 2007. Assessing trade-offs between carbon sequestration and timber production within a framework of multi-purpose forestry in Austria. Forest Ecology and Management 248, 64-79.

Shearman, P., Bryan, J., Laurance, W.F., 2012. Are we approaching 'peak timber' in the tropics? Biological Conservation 151, 17-21.

Shozugawa, K., Nogawa, N., Matsuo, M., 2012. Deposition of fission and activation products after the Fukushima Dai-ichi nuclear power plant accident. Environmental Pollution 163, 243-247.

Simmons, J.A., 2001. Radiation risks from inhaled alpha emitters. Radiation Physics and Chemistry 61, 629-630.

Sorrell, S., Speirs, J., Bentley, R., Miller, R., Thompson, E., 2012. Shaping the global oil peak: A review of the evidence on field sizes, reserve growth, decline rates and depletion rates. Energy 37, 709-724.

Steffen, W.L., 2004. Global change and the earth system: a planet under pressure. Springer, Berlin, New York.

Steinbeiss, S., Gleixner, G., Antonietti, M., 2009. Effect of biochar amendment on soil carbon balance and soil microbial activity. Soil Biology and Biochemistry 41, 1301-1310.

Stern, N., 2006. Stern review on the economics of climate change. Stern Review on the Economics of Climate Change, UK Treasury.

Strauss, F., Formayer, H., Asamer, V., Schmid, E., 2010. Climate change data for Austria and the period 2008-2040 with one day and km^2 resolution: Detaillierte Daten auf Gemeindeebene. Diskussionspapier des Institutes für nachhaltige Wirtschaftsentwicklung, Universität für Bodenkultur, Wien.

Tans, P., 2012. Trends in Atmospheric Carbon Dioxide. National Oceanic and Atmospheric Administration (NOAA), Earth System Research Laboratory (ESRL), USA.

Tatzber, M., Mutsch, F., Leitgeb, E., Englisch, M., Mentler, A., Gerzabek, M., 2011. Mid-Infrared Spectroscopy for Determinations of Carbonate in Soils-What is Important? American Laboratory 43, 13-17.

Tatzber, M., Stemmer, M., Spiegel, H., Katzlberger, C., Haberhauer, G., Gerzabek, M., 2007. An alternative method to measure carbonate in soils by FT-IR spectroscopy. Environmental Chemistry Letters 5, 9-12.

Terada, T., Yokohari, M., Bolthouse, J., Tanaka, N., 2010. Refueling Satoyama Woodland Restoration in Japan: Enhancing Restoration Practice and Experiences through Woodfuel Utilization. Nature and Culture 5, 251-276.

Trap, J., Bureau, F., Vinceslas-Akpa, M., Chevalier, R., Aubert, M., 2009. Changes in soil N mineralization and nitrification pathways along a mixed forest chronosequence. Forest Ecology and Management 258, 1284-1292.

Trumbore, S., 2009. Radiocarbon and Soil Carbon Dynamics. Annual Review of Earth and Planetary Sciences 37, 47-66.

Van Belle, J.F., 2006. A model to estimate fossil CO_2 emissions during the harvesting of forest residues for energy-with an application on the case of chipping. Biomass & Bioenergy 30, 1067-1075.

Van Deusen, P., 2010. Carbon sequestration potential of forest land: Management for products and bioenergy versus preservation. Biomass & Bioenergy 34, 1687-1694.

Vasilyeva, N.A., Abiven, S., Milanovskiy, E.Y., Hilf, M., Rizhkov, O.V., Schmidt, M.W.I., 2011. Pyrogenic carbon quantity and quality unchanged after 55 years of organic matter depletion in a Chernozem. Soil Biology and Biochemistry 43, 1985-1988.

Vesterdal, L., Schmidt, I.K., Callesen, I., Nilsson, L.O., Gundersen, P., 2008. Carbon and nitrogen in forest floor and mineral soil under six common European tree species. Forest Ecology and Management 255, 35-48.

Vetter, M., Wirth, C., Bottcher, H., Churkina, G., Schulze, E.D., Wutzler, T., Weber, G., 2005. Partitioning direct and indirect human-induced effects on carbon sequestration of managed coniferous forests using model simulations and forest inventories. Global Change Biology 11, 810-827.

Wikipedia, 2012. Biomasseheizkraftwerk. Wikipedia, Die freie Enzyklopädie. Available: http://de.wikipedia.org/w/index.php?title=Biomasseheizkraftwerk&oldid=103414951. Last accessed: 01st June, 2012.

Wilkinson, D.M., Nisbet, E.G., Ruxton, G.D., 2012. Could methane produced by sauropod dinosaurs have helped drive Mesozoic climate warmth? Current biology 22, R292-R293.

Wiseman, C.L.S., 2003. Organic Carbon Sequestration in Soils: An Investigation of Five Profiles in Hesse, Germany. Fachbereich Geowissenschaften/Geographie. Johann Wolfgang Goethe-Universität, Frankfurt am Main, 268 pages.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., Joseph, S., 2010. Sustainable biochar to mitigate global climate change. Nature Communications 1, 1-9.

Wu, H., Guo, Z., Gao, Q., Peng, C., 2009. Distribution of soil inorganic carbon storage and its changes due to agricultural land use activity in China. Agriculture, Ecosystems & Environment 129, 413-421.

Yokohari, M., Bolthouse, J., 2011. Keep it alive, don't freeze it: a conceptual perspective on the conservation of continuously evolving "satoyama" landscapes. Landscape and Ecological Engineering 7, 207-216.

Zalasiewicz, J., Smith, A., Williams, M., Gale, A., Brenchley, P., Evans, J., Knox, R., Riley, N., Gregory, F., Rushton, A., 2008. Are we now living in the Anthropocene? GSA Today 18, 4-8.

Zalasiewicz, J., Williams, M., Haywood, A., Ellis, M., 2011. The Anthropocene: a new epoch of geological time? Philosophical Transactions of The Royal Society A 369, 835-841.

Zeng, N., Zaitchik, B., 2012. Ecological carbon sequestration via wood harvest and storage: Can it be a viable climate mitigation and adaptation strategy? (EGU2012-11512). Conference contribution, European Geosciences Union General Assembly 2012. Geophysical Research Abstracts 14, Vienna.

Scientific publications

Paper 1

Paper 1: Carbon pools and temporal dynamics along a rotation period in *Quercus* dominated high forest and coppice with standards stands

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Abstract

Carbon pools in two *Quercus petraea* (sessile oak) dominated chronosequences under different forest management (high forest and coppice with standards) were investigated. The objective was to study temporal carbon dynamics, in particular carbon sequestration in the soil and woody biomass production, in common forest management systems in eastern Austria along with stand development. The chronosequence approach was used to substitute time-for-space to enable coverage of a full rotation period in each system. Carbon content was determined in the following compartments: aboveground biomass, litter, soil to a depth of 50 cm, living root biomass and decomposing residues in the mineral soil horizons. Biomass carbon pools, except fine roots and residues, were estimated using species-specific allometric functions. Total carbon pools were on average 143 Mg ha^{-1} in the high forest stand (HF) and 213 Mg ha^{-1} in the coppice with standards stand (CS). The mean share of the total organic carbon pool (TOC) which is soil organic carbon (SOC) differs only marginally between HF (43.4%) and CS (42.1%), indicating the dominance of site factors, particularly climate, in controlling this ratio. While there was no significant change in O-layer and SOC stores over stand development, we found clear relationships between living biomass (aboveground and belowground) pools and C:N ratio in topsoil horizons with stand age. SOC pools seem to be very stable and an impact of silvicultural interventions was not detected with the applied method. Rapid decomposition and mineralization of litter, indicated by low O-horizon pools with wide C:N ratios of residual woody debris at the end of the vegetation period, suggests high rates of turnover in this fraction. CS, in contrast to HF benefits from rapid resprouting after coppicing and hence seems less vulnerable to conditions of low rainfall and drying topsoil.

Keywords: Carbon dynamics, Soil carbon, Chronosequence, *Quercus petraea*, Coppice, High forest

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ABSTRACT

Carbon pools in two *Quercus petraea* (sessile oak) dominated chronosequences under different forest management (high forest and coppice with standards) were investigated. The objective was to study temporal carbon dynamics, in particular carbon sequestration in the soil and woody biomass production, in common forest management systems in eastern Austria along with stand development. The chronosequence approach was used to substitute time-for-space to enable coverage of a full rotation period in each system. Carbon content was determined in the following compartments: aboveground biomass, litter, soil to a depth of 50 cm, living root biomass and decomposing residues in the mineral soil horizons. Biomass carbon pools, except fine roots and residues, were estimated using species-specific allometric functions. Total carbon pools were on average 143 Mg ha^{-1} in the high forest stand (HF) and 213 Mg ha^{-1} in the coppice with standards stand (CS). The mean share of the total organic carbon pool (TOC) which is soil organic carbon (SOC) differs only marginally between HF (43.4%) and CS (42.1%), indicating the dominance of site factors, particularly climate, in controlling this ratio. While there was no significant change in O-layer and SOC stores over stand development, we found clear relationships between living biomass (aboveground and belowground) pools and C:N ratio in topsoil horizons with stand age. SOC pools seem to be very stable and an impact of silvicultural interventions was not detected with the applied method. Rapid decomposition and mineralization of litter, indicated by low O-horizon pools with wide C:N ratios of residual woody debris at the end of the vegetation period, suggests high rates of turnover in this fraction. CS, in contrast to HF benefits from rapid resprouting after coppicing and hence seems less vulnerable to conditions of low rainfall and drying topsoil.

1. Introduction

The increasing interest in renewable energy makes forests a potential source of biomass for energetic utilization. Recent studies in deciduous forests in north-eastern Austria focused on this aspect (Hochbichler, 2008; Hochbichler et al., 2009). These forests were traditionally managed as coppice with standards or high forest systems primarily to supply fuelwood for nearby settlements and financial returns for the forest owner from high quality timber. Their importance as a source of thermal energy diminished with the utilization of fossil fuels in the midst of the 19th century. Although fuel wood harvesting continued to the present, management goals have shifted generally towards high quality timber production. In the past, some of these forests were temporarily used as agricultural land, as indicated by historic field names (e.g. potato ground). Increasing biomass extraction as a source for thermal energy may have negative effects on ecosystem functions and on the capacity of forest ecosystems to sequester atmospheric carbon (C) and thus to offset anthropogenic CO_2 emissions. A better understanding of carbon dynamics in forest ecosystems is needed to avoid negative effects. Forests represent the largest C pools on earth (Vande Walle et al., 2001). Within temperate forest ecosystems, soils are typically the dominant pools of organic C. The contribution of the soils to the total C sink of forests is believed to increase in North and Central Europe as a consequence of increased litter fall (Liski et al., 2002). Litter fall represents the largest flux of C from above ground biomass to the soil where decomposing litter is a major component of soil organic matter (SOM). SOC and total soil nitrogen (N_t, subsequently denoted as "N" throughout this paper) are key components of SOM, covaried and incorporated into a range of organic compounds e.g. humic acids, fulvic acids, carbohy-

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drates and lipids. Quantity and quality of SOM (i.e. its degradability and thus the release of sequestered plant nutrients) is again considerably influenced by forest management (Chen and Xu, 2005) and environmental conditions, such as soil temperature and moisture. Root turnover, bioturbation and infiltration of dissolved organic carbon (DOC) are processes favouring translocation of C into deeper soil horizons. C pools in deeper horizons are typically associated with minerals, leading to turnover rates >100 years, while topsoil horizons are most reactive in terms of soil respiration and turnover occurs in a few months to several years (Gaudinski et al., 2000). C mineralization, as a part of this turnover process, is controlled by a range of parameters such as soil microbiology, soil texture, initial litter quality (inherent C:N ratio) and soil moisture regime (Giardina et al., 2001).

The effects of forest management (Lal, 2005; De Vries et al., 2006, 2009; Seidl et al., 2007; Nabuurs et al., 2008; Foley et al., 2009) and climate change (Bolte et al., 2009; Lindner et al., 2010) on carbon sequestration have been widely discussed. The intrinsic spatial variability of forest ecosystem C pools is controlled by soil type, forest management and resulting vegetation cover, as well as environmental factors (e.g. mean annual temperature, precipitation). Consequently, the knowledge of a range of local parameters is essential for estimating pools and fluxes. Therefore the extrapolation of local datasets to characterize even adjacent ecosystems is very limited. This study is intended to contribute site specific data on carbon dynamics of forests and silvicultural systems in a specific region, with special emphasis on the potential of woody biomass production for energetic utilization. Long-term studies or space-for-time substitutions are needed to describe carbon dynamics across the entire life span (rotation period) of a managed forest ecosystem. Understanding the processes and factors controlling C balance and temporal dynamics will help to mitigate losses and maximize sequestration and consequently lead to effective C management in forest ecosystems.

The objective of this study was to investigate temporal carbon dynamics in common forest management systems of coppice with standards and high forest in the eastern part of Austria along a stand development gradient in view of carbon sequestration and woody biomass production. Our hypothesis was that carbon stores remain relatively constant across all pools in coppice with standards system in contrast to the high forest system and therefore we assume that substantial CO_2 emissions, induced by silvicultural interventions, are less likely to occur. We further investigated N pools in the soil to estimate the impacts of forest stand development and soil properties on C:N ratios.

2. Materials and methods

2.1. Study area

The forests in our study are situated in north-eastern Austria, approx. 40 km north of Vienna. In the selection of our study plots we considered the availability of data on management history, access and support by the land owners. The coppice with standards system studied lies near Wolkersdorf (48°25′N 16°34′E), while the high forest is located near Hollabrunn (48°33′N 16°16′E). The plots in both areas are within 6 km of each other. The mean annual temperature ranges between 8.8 °C (Hollabrunn) and 9.5 °C (Wolkersdorf) with January being the only month with a mean temperature below zero in both study areas. They receive 500 and 525 mm of annual precipitation, respectively. Total N deposition rates (1996–2005) were reported to range between 7.6 and 9.4 kg ha a^{-1} (Smidt, 2007) across our study region. Both locations are surrounded by extensive agricultural land, which is likely the main source of deposited N. Elevation is between 250 and 300 m a.s.l. The topography is generally rolling hills (<15°) with some gentle slopes resulting from postglacial erosions. The parent material consists of gravel, sand and silt built up during the Pannonium (between 7.2 and 11.6 Ma before present) as a result of the early development of the Danube River at the Hollabrunn plots. Consequently, a variety of soil types can be found, e.g. cambisols, luvisols, chernozems and even stagnosols. Younger aeolian deposits of loess (Pleistocene) led to periglacial formation of chernozems at the Hollabrunn plots. The soil types of our plots are eutric cambisol with a considerable amount of coarse material (⩽40% volume) and sandy clay loam texture near Hollabrunn and both haplic and vermic chernozems with loamy texture near Wolkersdorf (IUSS Working Group WRB, 2006). The forest patches containing our plots are surrounded by arable land at both study locations, typically on loess derived soils, which are among the most fertile in Austria. Oak–hornbeam forests are typical for the region (*Primulo veris-Carpinetum*), *Corylus avellana* is partially abundant in the understorey. The dominating tree species (overstorey) is *Quercus petraea* in all study plots.

High forest (HF) and Coppice with standards (CS) are the most common silvicultural management systems for broadleaved forest ecosystems in north-eastern Austria. However, these systems were locally adapted over time as described below. *Quercus* dominated high forests aim at producing quality timber with a diameter of at least 30 cm, at rotation periods of approximately 120 years, followed by shelterwood cuts and natural regeneration. Thinning operations and harvesting residues provide biomass for thermal utilization. Thinning is performed 4 times, at 30, 50, 70 and 90 years.

Quercus–Carpinus coppice with standards is a woodland management system where among coppice some trees are left in four age-classes to grow as larger size timber, called "standards", aiming both at producing biomass for thermal utilization as well as timber for trades. This multi-aged traditional system supports sustainable production of timber and non-timber forest products, while enhancing ecosystem diversity and wildlife habitat (Nyland, 2002). The rotation period for coppice (understorey) is typically 30 years (Hochbichler, 1993, 2008), hence holding a middle position between planted short rotation woody crops (SRWC) (Dickmann, 2006) and traditional high forests. The system is characterized by cyclic vegetative and genetic regeneration (Hochbichler, 2008). Sprouting occurs rapidly after harvest and standards provide shade and being a source for seeds as backup if sprouting is not successful. Individual standards are managed in four age classes (30–60, 60–90, 90–120, and 120+ years) and harvested depending on certain criteria (e.g. market value, tree health, stand density).

We were able to include an outgrown coppice plot aged 50 years to widen the scope for temporal dynamics. Irregular harvesting of standards and rotation periods up to 50 years (outgrown coppice) led to divergent silvicultural structures with diffuse standards (Hochbichler, 1993). The plots were established during summer 2007 as permanent sample plots for aboveground biomass monitoring and are part of a framework to investigate biomass and carbon pools in this region (Hochbichler et al., 2009).

2.2. Field methods

We established a chronosequence as a space-for-time substitution (Pickett, 1989) of five plots in each study area, covering important stand development phases (Bormann and Likens, 1979) in HF and different ages in CS (Table 1). The plots within a chronosequence set have the same site characteristics (microclimate, parent material, soil type and structure, elevation, topography, species community) to retain a reasonable signal-to-noise ratio and based on inventory data from the past, we assume that the stands follow convergent succession trajectories (Walker et al., 2010). However, we are aware that the proposed approach has intrinsic limitations such as regional averaging, assumption of development without major

Table 1
Organic carbon stocks as well as stand and soil characteristics for study plots in two chronosequence sets of oak dominated high forest on eutric cambisol and oak–hornbeam coppice with standards on chernozem. Ages for coppice with standards are given for understorey. Development phases are described in Bormann and Likens (1979). Standard errors are given in parenthesis. Topsoil = 0–10 cm, subsoil = 40–50 cm; fine roots Ø < 2 mm, coarse roots Ø > 2 mm. † = end of rotation period; ‡ = outgrown coppice.

High forest	11 years	32 years	50 years	74 years	91 years
Development phase	Reorganization	Aggradation	Aggradation	Aggradation	Transistion
Aboveground carbon stock (Mg ha^{-1})	12.1	58.1	69.8	77.1	74.8
Belowground carbon stock (Mg ha^{-1})	75.4	84.0	99.7	87.2	76.2
Overstorey parameters (DBH > 8 cm)					
Stand density (no. ha^{-1})	13	1625	575	288	236
Basal area (m^{-2} ha^{-1})	0.8	18.2	19.6	19.1	16.9
Lorey's mean height (m)	16	13	18	20	22
DBH (quadratic mean diameter) (cm)	28	12	21	29	30
% *Quercus petraea* (basal area)	100.0	90.3	100.0	92.1	92.9
Understorey parameters (DBH < 8 cm)					
% *Quercus petraea* (basal area)	99.2	99.6	50.0	0.0	32.1
Root carbon stocks					
Coarse roots carbon stock (Mg ha^{-1})	4.4	9.9	14.5	16.3	14.4
Fine roots carbon stock (Mg ha^{-1})	7.3 (0.6)	10.2 (1.9)	12.9 (2.7)	8.7 (1.7)	5.4 (0.7)
Intrinsic soil parameters					
Stone content [volume] (%)	20.5 (3.6)	8.2 (1.3)	13.9 (2.5)	9.3 (1.6)	9.6 (1.3)
Carbonate content topsoil (Mg ha^{-1})	0.5 (0.5)	0.0	0.0	0.0	0.0
Carbonate content subsoil (Mg ha^{-1})	4.6 (4.6)	0.0	70.0 (38.5)	3.7 (3.7)	0.0
pH ($CaCl_2$) topsoil	4.5 (0.3)	3.7 (0.1)	4.2 (0.2)	4.5 (0.2)	4.2 (0.2)
pH ($CaCl_2$) subsoil	4.6 (0.3)	4.1 (0.6)	5.2 (0.5)	4.8 (0.3)	4.4 (0.1)
Coppice with standards	**1 year**	**15 years**	**26 years**	**31 years**	**50 years**
Development phase (understorey)	Reorganization	Aggradation	Aggradation	Aggradation †	Aggradation ‡
Aboveground carbon stock (Mg ha^{-1})	69.3	55.4	96.7	118.4	134.0
Belowground carbon stock (Mg ha^{-1})	125.6	100.9	129.2	112.3	116.3
Overstorey parameters (DBH > 8 cm)					
Stand density (no. ha^{-1})	32	81	56	84	68
Basal area (m^{-2} ha^{-1})	10.2	7.7	10.8	10.8	13.4
Lorey's mean height (m)	21	20	22	25	21
DBH (quadratic mean diameter) (cm)	36	35	49	41	50
% *Quercus petraea* (basal area)	100.0	72.7	78.9	69.4	68.2
% *Carpinus betulus* (basal area)	0.0	27.3	21.1	19.4	30.2
Understorey parameters (DBH < 8 cm)					
% *Carpinus betulus* (basal area)	0.0	99.4	80.9	76.0	88.0
Root carbon stocks					
Coarse roots carbon stock (Mg ha^{-1})	12.2	16.1	17.3	22.5	12.7
Fine roots carbon stock (Mg ha^{-1})	6.0 (1.2)	5.8 (0.7)	4.5 (0.6)	8.0 (2.9)	6.2 (0.4)
Intrinsic soil parameters					
Stone content (volume) (%)	0.1 (0.0)	1.1 (0.4)	0.1 (0.1)	0.1 (0.0)	0.4 (0.1)
Carbonate content topsoil (Mg ha^{-1})	0.0	0.9 (0.9)	2.4 (2.4)	0.7 (0.7)	0.4 (0.4)
Carbonate content subsoil (Mg ha^{-1})	304.5 (58.3)	72.6 (45.7)	172.9 (65.3)	20.0 (15.3)	127.3 (49.7)
pH ($CaCl_2$) topsoil	5.6 (0.3)	5.0 (0.3)	5.5 (0.3)	5.3 (0.3)	5.1 (0.3)
pH ($CaCl_2$) subsoil	7.4 (0.9)	5.5 (0.4)	6.7 (0.4)	5.8 (0.3)	6.5 (0.4)

disturbances or ignoring site specific parameters when interpreting results. Variation between study plots in the same stage of development is ignored, unless considering two or more chronosequence series. Re-sampling, as suggested by Foster and Tilman (2000) could be applied to overcome some of these limitations and to gain additional insights into successional processes. Therefore, our plots were selected carefully, considering management history including disturbances (e.g. windthrow events) reconstructed from operation manuals, species composition, proximity to other species communities, ground vegetation, local climatic factors and topography as well as soil properties. Plot size was set at 40 × 40 m, except in the oldest high forest and in the youngest coppice with standards plots where it was extended to 50 × 50 m, according to Hochbichler (2008). Nine long-term sample points were established along a systematic grid in each plot and durably marked.

2.3. Biomass inventory and estimation

Tree seedlings, shrubs and bushes were recorded within a radius of 1.41 m from the sample point (= 6.25 m^2). All trees, shrubs and bushes >1.3 m tall and with a diameter at breast height (DBH) <8 cm were recorded within a circumferential distance of 2.8 m (= 25m^2). Trees and shrubs with a DBH >8 cm were fully recorded within the sample plot. The following parameters were assessed: tree height, DBH (if >8 cm), species, standing deadwood. The stem diameter in 10 cm above ground (D10) was recorded for all woody species of more than 20 cm height and with a DBH <8 cm. The main species of herbaceous ground vegetation was determined where occurring and ground cover percentage was estimated. Deadwood and herbaceous ground vegetation were neglected for biomass carbon pools due to their low abundance.

Aboveground biomass of trees and shrubs (dry mass) was estimated using allometric functions from Hochbichler (2008) and inventory data. Species-specific parameters not assessed on site were taken from Pertlik (1982), Hochbichler et al. (1994, 2006), Glück (1996), Bellos (2000), Laschober (2000) and Hochbichler (2002, 2008). Allometric functions, based on the relationship between stem diameter (DBH or D10) of a single individual and its root mass, were used to estimate coarse root (>2 mm) biomass. We used individual parameters for *Quercus* sp. and *Carpinus betulus*

(Offenthaler and Hochbichler, 2006), *Fraxinus excelsior* (Hochbichler and Putzgruber, 2004), *Fagus* sp. (Pellinen, 1986) and for all trees and shrubs <4 m tall (Jakucs, 1985; Pellinen, 1986; Drexhage and Colin, 2001; Van Hees and Clerkx, 2003). C content was estimated by assuming a C proportion of 50% of dry weight of woody biomass. This assumption is justified for *Quercus* sp. based on the assessment of Lamlom and Savidge (2003) for two North American *Quercus* species which showed C contents (w/w) of slightly less than 50%. We verified the C content in our study on five randomly selected root samples using a CHN (Carbon–Hydrogen–Nitrogen) analyzer and yielded results between 48.5% and 50.3%.

2.4. Soil sampling and preparation

Soil samples were collected during July and August in 2007 and 2008 using a tubular soil corer with 70 mm core diameter to a depth of >50 cm. The importance of considering the deeper horizons >20 cm when studying soil C changes has recently been pointed out (Diochon et al., 2009). Two samples were taken at each sample point along a north–south transect, at a distance of 2 m from the centre. Samples were immediately cooled and stored at 4 °C until further processing in the lab.

Soil cores were divided into six geometric horizons, i.e. O-horizon, 0–5, 5–10, 10–20, 20–40 and 40–50 cm soil depth. Corresponding horizons of the two samples per sample point were pooled prior to sieving of soil using a 2 mm mesh sieve. Living roots, coarse material >2 mm and decaying organic matter was separated from the mineral soil for each soil horizon and oven dried. The O-horizon was separated from the mineral soil, oven dried and subsequently ground for chemical analysis. Bulk density (ρ) is commonly calculated from oven-dry mass of mineral soil <2 mm (Gaudinski et al., 2000; Kulmatiski et al., 2003; Hopmans et al., 2005; Ma et al., 2007; Nilsen and Strand, 2008; Vesterdal et al., 2008; Diochon et al., 2009) but sometimes divergent soil fractions were used where soil properties are unsuitable for standard methods (Hart et al., 2006; Van Miegroet et al., 2007; Watanabe et al., 2009). However, we determined bulk density gravimetrically by dividing oven-dry mass (<2 mm) by the core segment volume corrected for the volume of rock fractions. Rocky coarse material density at the study plots was determined to be 2.59 g cm^{-3}. Fine root masses were derived directly from soil samples by determining the dry mass per core segment and projection to plot level for each horizon.

2.5. Analysis of soil chemical properties

Chemical analyses were performed on sieved soil samples (<2 mm) and ground O-layer using standard methods. Soil pH was determined in 0.01 M $CaCl_2$ and in distilled water, following the Austrian standard L 1083-99 (1999). Total soil C (C_t) was determined by dry combustion using a LECO SC-444 analyzer (Leco Corp., St. Joseph, MI) according to ON L 1080-99 (1999). Inorganic C (C_i) was measured gas-volumetrically by the Scheibler Method (ON L 1084-99, 1999) at samples showing a pH ($CaCl_2$) > 6 and subtracted from C_t in order to retrieve organic carbon (C_{org}) contents. Total nitrogen (N_t) was determined according to Kjeldahl using a Kjeltec 2300 Analyzer Unit (Foss, Hillerød, Denmark) following ON L 1082-99 (1999). Soil C concentration and soil mass were determined for each sample before averaging as suggested by Conen et al. (2005). The C:N ratio was calculated as the quotient of C and N concentrations.

2.6. Statistical analysis

One-way ANOVA followed by the Tukey-test ($P < 0.05$) was used to compare plots in different development stages, i.e. representing a chronosequence. Principal component analysis (PCA) was carried out to identify main drivers of stand differences along a development sequence. All statistical analyses were carried out with SPSS 17.0.0 (23.08.2008) and Sigmaplot 10.

3. Results

3.1. Biomass

Living biomass was strongly influenced by forest management and therefore shows clear differences between oak dominated high forest (HF) and oak–hornbeam coppice with standards system (CS). The average biomass C pool (standing woody plants + roots) was 74(14) Mg ha^{-1} (mean ± 1 standard error (SE) is presented in parentheses throughout this paper unless otherwise indicated) in HF and 114(15) Mg ha^{-1} in CS, where the older 31- and 50 year stands contribute to the high value. We found rising stores with increasing age in HF, culminating at approximately 70 years, when a pronounced understorey develops. The biomass of the standards in CS is the cause for relatively high living biomass stores in the one year old stand (85 Mg ha^{-1}) in contrast to the 11 year old HF stand (19 Mg ha^{-1}).

3.2. Root C pools and root-to-shoot ratio

On average, fine root C pools decreased with increasing stand age in HF ($R = -0.28$; $p < 0.01$) but remained constant in CS. However, this general statement obscures temporal dynamics. In fact, corresponding to stand development stages, fine root biomass increased after stand reorganization, culminated at an age of 31 (CS) and 50 years (HF) and subsequently decreased with stand ageing. In accordance with increasing aboveground biomass stores, coarse root C pools increased with age in HF ($R = 0.87$; $p = 0.53$), accounting for 8.0(0.9)% of total C pool and no trend was observed in CS, where coarse root C pools accounted for 7.8(1.0)%, respectively. Typically root-to-shoot ratios indicate higher C accumulation rates belowground in the stand reorganization phase. The ratio between aboveground biomass and root C accumulation differs distinctly between the two stand management systems HF and CS (Fig. 1). The initial decrease, typical for most stand developments from regeneration to old-growth states, was not observed in the CS system where standards contribute to significant aboveground biomass during the stand reorganization phase. As a consequence, C root/shoot ratios are in equilibrium throughout the rotation period. However, the effect of standards harvesting could be observed by a slightly higher ratio in the 15-years old stand compared with the one-year old stand (Fig. 1). On average, the root

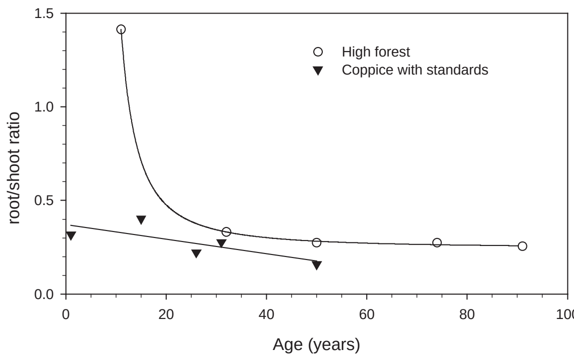

Fig. 1. Relationship between carbon root/shoot ratio and stand age for HF and CF chronosequence. The solid lines represent a hypothetic pattern.

C pool represented 28.0(3.0)% of total phytomass C stores when excluding the youngest HF stand where the root C pool was 1.6 times as high as aboveground phytomass stores.

3.3. Soil C pool

Mean SOC pools (belowground C pools excluding roots and organic residues) ranged from 53 to 69 Mg ha^{-1} in HF and 72–104 Mg ha^{-1} in CS. Standard errors of SOC determination ranged from 1.9 Mg ha^{-1} (32 year old stand) to 5.7 Mg ha^{-1} (50 years) in HF and from 3.2 Mg ha^{-1} (31 years) to 9.8 Mg ha^{-1} (1 year) in CS. SOC pools steadily decreased with increasing soil depth, except in the 1 and 50 year old CS plots (Fig. 2). C stores of decaying residues (e.g. fruit capsules, roots) ranged from 3.1(0.2) to 7.6(3.0) Mg ha^{-1} in HF and from 3.5(0.5) to 9.5(2.3) Mg ha^{-1} in CS. In HF, a small proportion, 11%, of all subsoil samples (40-50 cm soil depth) contained carbonate (140.9(52.3) Mg ha^{-1}), while in CS we found carbonate in 53% of all subsoil samples (261.5(31.7) Mg ha^{-1}). In the topsoil horizon (0–10 cm), carbonate was only found in 9% of the samples in CS plots (10.0(4.0) Mg ha^{-1}, see Table 1). Bulk density (ρ) significantly decreased with increasing C and N stores in HF ($R = -0.74$ and -0.67; $p < 0.01$) and in CS ($R = -0.72$ and -0.62; $p < 0.01$), underlining accumulation in topsoil horizons with lower bulk density.

3.4. Total carbon pools

The total C pool was on average 143 Mg ha^{-1} (87–170 Mg ha^{-1}) in HF and 213 Mg ha^{-1} (156–250 Mg ha^{-1}) in CS (Fig. 3). Included in these estimates are aboveground standing woody biomass, litter and humus (O-layer), roots, decaying organic matter and SOC to a depth of 50 cm. The ratio of aboveground/belowground pools steadily increases with increasing age, (0.16–0.99 in HF and 0.55–1.16 in CS) indicating aboveground biomass accumulation. The ratio is always higher in CS throughout the whole stand development (up to 50 years in our study). The mean share of the total organic carbon pool (TOC) that is SOC only marginally differs between HF (43.4(5.7)%) and CS (42.1(3.7)%). In HF, fine root C pool accounted for 6.4(0.9)% of the total carbon pool, while in CS it accounted only for 2.9(0.3)%. On average, root C pool represented 21.8(1.8)% of the total belowground C pool (SOC, roots, decaying organic matter).

3.5. C:N ratio

The C:N ratio differs greatly between O-horizon and mineral soil. Mean C:N ratios in HF were 35.2(1.4) (O-horizon) and 15.0(0.3) (mineral soil) and in CS 31.8(4.1) and 12.1(0.3), respectively. The C:N ratios narrowed significantly ($p < 0.05$) with increasing soil depth in both management systems. However, a steady significant decrease throughout the profile (O-layer down to 50 cm) was only found in HF. C:N ratios in CS decreased significantly down to 20 cm soil depth. The 20–40 cm and 40–50 cm strata did not differ significantly due to high quasi-temporal (space-for-time substitution) variability, high carbonate and organic matter contents in the subsoil, as well as indicators for increased bioturbation. The C:N ratio remains fairly constant during stand development in the O-horizon of HF while a steady decreasing tendency was observed in mineral topsoil horizons (0–20 cm). However, CS showed a different pattern along stand development, which is most observable in the O-horizon. Mean C:N values drop from 35.9(1.4) to 27.5(0.0) in the first development phase, from 1 to 15 years, from which a steady increase to 36.3(0.3) at the age of 50 years was observed (Table 2). The same trend was found in the uppermost mineral soil horizon (0–5 cm), but differences are not significant at $p < 0.05$. In HF, the C:N ratio is stronger correlated with C ($R = +0.70$, $p < 0.01$) in comparison to N ($R = +0.17$, $p < 0.01$). In the CS system, C:N ratio is stronger correlated with N ($R = -0.33$, $p < 0.01$) in comparison to C ($R = +0.20$, $p < 0.01$).

3.6. Principal component analysis of soil variables

The first two factors explained respectively 57% and 22% of the total variance in the PCA of soil parameters across both chronosequence series (Fig. 4). Factor 1 discriminated samples according to chemical soil parameters, particularly by contents of carbonate,

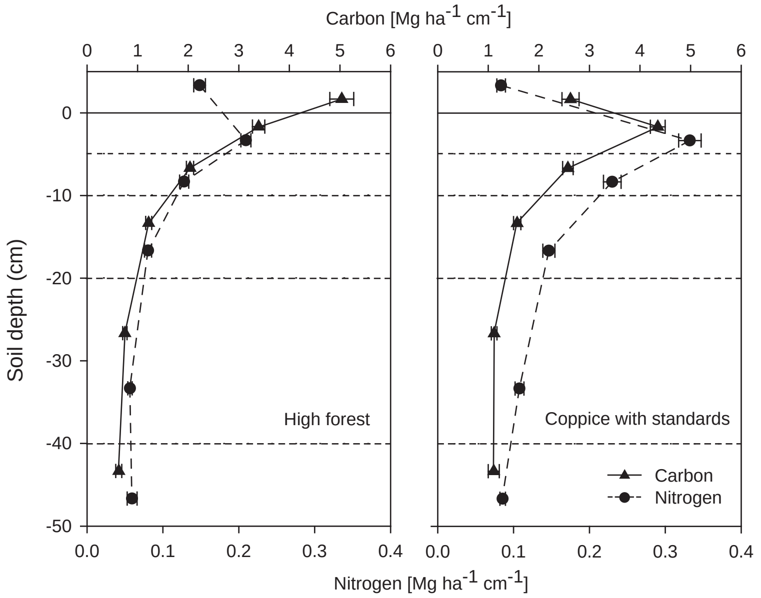

Fig. 2. O-layer and mineral soil pools of carbon and nitrogen for high forest and coppice with standards standardized to 1 cm soil depth. Error bars indicate the standard error of the mean (± 1 SE). Horizontal reference lines at 0, 5, 10, 20 and 40 cm soil depth indicate the O-layer and sampled soil core sections.

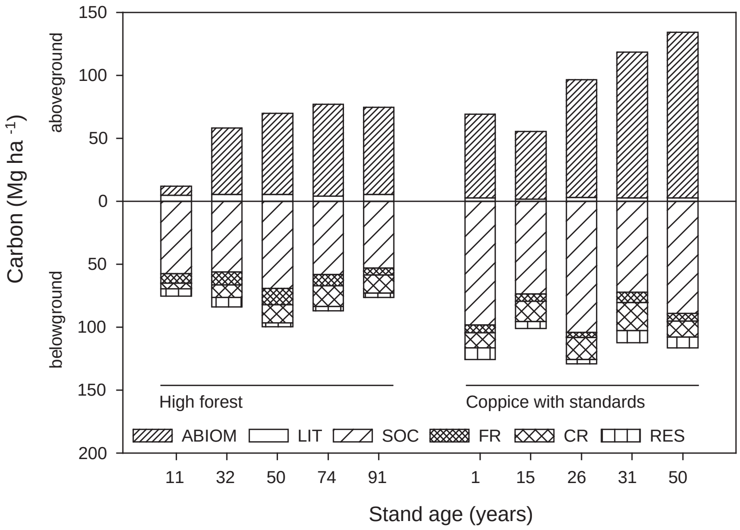

Fig. 3. Total carbon pools for HF and CS, separated into aboveground (aboveground biomass [ABIOM], litter [LIT]) and belowground (soil organic carbon [SOC], fine roots <2 mm [FR], coarse roots >2 mm [CR], fresh or partially decomposed residues [RES]) compartments for each plot in the two chronosequence sets.

SOC, N and pH-value (H_2O), which showed a good correlation. Factor 2 therefore distinguished stands primarily among physical soil properties (bulk density ρ, gravel content) and by some chemical properties (C:N ratio and to a certain extent ΔpH). Oblique rotation (Direct Oblimin) was applied to underline soil parameter's assignment to the PCA factors. Bartlett's test of sphericity revealed a result of $\chi^2(28) = 687.11$; $p < 0.001$, which together with the KMO-value of 0.705 confirms the feasibility of the applied method. No overlap between the two chronosequence series underpins the influence of different soil types on our results. Trends with age were generally not clearly observed, considering only soil parameters. However, ΔpH (pH (H_2O) minus pH ($CaCl_2$)) seems to increase from the 50 years plot to the 91 years plot of HF, indicating a higher potential acidity in older stands. C:N values in mineral soil seem to be well represented by O-layer C:N values also shown in Fig. 4, indicating their importance in controlling mineral soil C:N ratios.

4. Discussion

4.1. Aboveground and total C stores

Total ecosystem C stores increased constantly with age, regardless of the silvicultural management system, where aboveground biomass accumulation was the driving factor. On average, 33% less carbon was stored in the HF system as compared to the CS system. While aboveground biomass, coarse roots and SOC showed the same pattern, an opposite trend was observed for O-layer and fine root C pools with in total 1.6 times greater stores in HF. In general, soil and O-layer carbon stores are relatively low in comparison to the mean pool of Austria's forests (120 Mg ha^{-1}; estimated with data from Englisch (1992)), as a consequence of the warm and dry climate in the study area and the stand species composition. Between system differences were clearly larger than within chronosequence variations. CS outperformed HF in terms of net primary production (NPP), compensating lower basal areas of overstorey (DBH >8 cm) with higher stand density. Thinning operations may contribute to these dynamics, by removing aboveground biomass in regular intervals in HF while only one intervention takes place in CS, when harvesting coppice and selected standards. Irregular cuts in combination with the mortality pattern of the CS-system; i.e. increasing mortality under standards when the understorey canopy closes, likely lead to lower stores in the 10 year old stand as compared to the 1 year old stand in our particular chronosequence. While C stores seem to reach a more or less steady state equilibrium in HF at an age of approximately 70 years, C stores in CS still increase at the end of the rotation period, particularly in aboveground biomass. As a consequence, higher aboveground C sequestration rates may only be realized in CS when extending the rotation period. Foley et al. (2009) reported that forests with a higher productivity will sequester more carbon (which would be creditable by carbon offset programs for instance) supporting our conclusion.

4.1.1. O-horizon and SOC pools

Decreasing SOC pools with increasing soil depth suggest ongoing mineralization and transition from labile C fractions towards more recalcitrant compounds often associated with minerals. Topsoil- and O-horizon C pools, holding the majority of labile C, were comparatively low. The most striking difference between HF and CS was found in the O-layer. Lower C pools in CS O-horizon as compared to topsoil horizon (0–5 cm) in combination with a wide C:N ratio suggests faster decomposition of leaves and thus mineralization in CS. Observed vermic conditions *in situ* (e.g. earthworm casts) in some of our CS plots support this hypothesis. Earlier studies confirmed that earthworm abundance could significantly increase leaf decomposition rates (Cortez, 1998). Bioturbation may also be a factor responsible for elevated C stores in the subsoil horizon in 1 and 50 year CS plots (Table 2). Vermic conditions were observed in both plots. In the subsoil horizon (40–50 cm), SOC was significantly correlated with decaying residues ($R = +0.57$, $p < 0.05$), originating predominantly from roots. Formation of Ca-bridges between SOM and clay minerals (Muneer and Oades, 1989) and thus SOC stabilization might be another reason for higher SOC stores in subsoil as compared to the adjacent 20–40 cm soil horizon. Foliage C:N ratio is an essential parameter controlling litter decomposition (Zhang et al., 2008). More favourable fresh litter C:N ratios in CS, as a consequence of a higher proportion of understorey dominating *C. betulus* with narrower C:N ratios of around 39 (Jacob et al., 2010), may also contribute to rapid litter decomposition and hence lower C stores in CS. *Q. petraea* fresh leaf litter, the

Table 2
Mean and standard error (in parenthesis) of the bulk density, organic carbon content, nitrogen content and C:N ratio for each stratum and plot in the chronosequence sets HF and CS. Carbon and nitrogen contents are standardized to 1 cm in mineral soil strata. Significant differences within a stratum and different age at $P < 0.05$ are indicated with different letters where 'a' denotes the lowest value.

Stratum	Oak dominated high forest (HF)					Oak–hornbeam coppice with standards (CS)				
O-horizon	Age (y)		C (g m^{-2})	N (g m^{-2})	C:N	Age (y)		C (g m^{-2})	N (g m^{-2})	C:N
	11		471.4 (55.7)	13.5 (1.7)	37.7 (5.1)	1		268.5 (41.5)	7.7 (1.3)	35.9 (1.4)c
	32		543.4 (34.4)	16.2 (1.1)	33.6 (0.4)	15		184.2 (30.0)	6.7 (1.1)	27.5 (0.0)a
	50		538.8 (58.9)	16.4 (2.1)	35.2 (5.0)	26		311.3 (37.0)	10.7 (1.3)	29.0 (0.0)b
	74		399.2 (46.3)	11.2 (1.4)	35.8 (0.6)	31		269.7 (47.1)	9.0 (1.7)	30.4 (0.6)b
	91		565.1 (55.6)	16.9 (1.8)	33.6 (1.0)	50		279.5 (23.8)	7.7 (0.7)	36.3 (0.3)c
Mineral soil (cm)	Age (y)	Bulk density (g cm^{-3})	C (g m^{-2} cm^{-1})	N (g m^{-2} cm^{-1})	C:N	Age (y)	Bulk density (g cm^{-3})	C (g m^{-2} cm^{-1})	N (g m^{-2} cm^{-1})	C:N
0–5	11	1.01 (0.03)b	417.8 (30.4)c	24.0 (1.6)b	17.4 (0.7)b	1	1.02 (0.04)b	479.2 (28.9)bc	36.1 (2.9)ab	13.8 (1.2)
5–10		1.61 (0.10)b	208.1 (20.2)	11.5 (1.4)	18.1 (1.1)b		1.33 (0.05)	243.0 (21.3)	21.3 (2.9)	12.6 (1.3)
10–20		1.74 (0.08)	108.4 (10.9)	6.7 (0.7)a	16.2 (2.0)		1.33 (0.04)	134.3 (11.8)a	12.8 (1.6)	11.3 (1.2)
20–40		1.82 (0.08)	68.3 (3.3)	5.5 (0.5)	12.4 (1.0)		1.31 (0.03)a	109.5 (12.3)	10.5 (0.7)	10.4 (1.1)
40–50		1.80 (0.20)	52.9 (9.5)	6.6 (0.6)	8.0 (0.7)		1.17 (0.03)a	192.3 (36.7)ab	9.2 (0.3)	20.9 (3.9)
0–5	32	0.73 (0.03)a	345.0 (28.1)	20.6 (1.5)ab	16.8 (0.7)ab	15	0.93 (0.02)ab	339.0 (26.6)a	27.0 (2.7)a	12.8 (0.4)
5–10		1.31 (0.05)a	190.3 (9.9)	10.7 (0.8)	18.1 (1.0)b		1.20 (0.37)	238.7 (23.7)	20.8 (1.9)	11.5 (0.4)
10–20		1.68 (0.07)	107.9 (5.5)	7.0 (0.5)ab	15.9 (1.2)		1.36 (0.03)	144.5 (14.7)a	13.5 (1.4)	10.7 (0.2)
20–40		1.66 (0.07)	71.9 (4.7)	6.2 (0.4)	11.7 (0.7)		1.47 (0.03)b	95.3 (11.9)	9.6 (1.2)	9.9 (0.2)
40–50		1.89 (0.08)	60.8 (4.9)	6.0 (0.4)	10.1 (0.3)		1.48 (0.08)b	73.0 (9.3)ab	7.0 (0.6)	10.4 (0.7)
0–5	50	0.93 (0.08)ab	362.5 (15.7)bc	20.5 (1.0)ab	17.8 (0.6)b	26	1.00 (0.04)b	525.0 (30.9)c	42.9 (2.6)b	12.3 (0.4)
5–10		1.29 (0.05)a	223.5 (18.0)	13.6 (1.5)	17.4 (1.8)ab		1.21 (0.03)	293.3 (27.4)	27.3 (3.4)	11.2 (0.5)
10–20		1.56 (0.07)	150.7 (18.8)	10.7 (1.8)ab	14.8 (0.7)		1.31 (0.04)	205.2 (19.3)b	18.8 (2.4)	11.2 (0.4)
20–40		1.74 (0.06)	101.1 (15.4)	7.0 (0.9)	14.6 (1.2)		1.34 (0.03)a	149.1 (15.6)	14.0 (2.1)	11.3 (0.8)
40–50		1.65 (0.12)	52.8 (13.3)	4.8 (0.9)	10.6 (1.1)		1.30 (0.05)ab	100.2 (14.3)ab	9.3 (1.1)	11.5 (1.7)
0–5	74	0.88 (0.64)ab	272.6 (13.8)a	18.2 (1.5)a	15.5 (1.2)ab	31	0.89 (0.05)ab	381.0 (18.6)ab	31.8 (1.7)ab	12.1 (0.4)
5–10		1.29 (0.04)a	216.4 (17.6)	14.1 (1.5)	15.9 (1.2)ab		1.27 (0.03)	245.9 (19.0)	22.3 (1.9)	11.1 (0.4)
10–20		1.47 (0.18)	125.6 (18.0)	7.4 (0.9)ab	16.5 (1.5)		1.29 (0.03)	142.0 (8.0)a	14.4 (1.3)	10.5 (1.1)
20–40		1.75 (0.08)	78.6 (13.2)	5.3 (0.6)	15.0 (1.7)		1.38 (0.01)ab	93.6 (5.7)	10.9 (0.5)	8.6 (0.4)
40–50		1.78 (0.09)	50.7 (6.7)	4.6 (0.9)	12.0 (1.6)		1.32 (0.05)ab	60.7 (4.7)a	8.6 (0.5)	7.2 (0.6)
0–5	91	0.90 (0.07)ab	297.9 (18.3)ab	21.3 (1.3)ab	14.0 (0.3)a	50	0.81 (0.04)a	451.7 (16.0)bc	28.5 (3.8)a	14.9 (1.3)
5–10		1.41 (0.06)ab	186.9 (13.4)	14.8 (1.1)	12.7 (0.3)a		1.24 (0.05)	266.6 (26.2)	23.5 (2.6)	11.7 (0.8)
10–20		1.73 (0.05)	116.2 (6.9)	9.3 (0.8)b	12.7 (0.6)		1.33 (0.02)	159.9 (15.4)ab	13.7 (1.5)	12.0 (0.9)
20–40		1.79 (0.05)	69.7 (5.0)	5.8 (0.4)	12.4 (1.3)		1.38 (0.02)ab	110.4 (6.5)	9.0 (1.0)	13.5 (1.5)
40–50		1.83 (0.07)	45.8 (7.2)	8.6 (3.9)	8.9 (1.4)		1.37 (0.05)ab	127.8 (15.5)b	8.7 (1.1)	15.8 (2.1)

dominating litter fraction at HF, has a much wider C:N ratio of 64 (Bocock, 1964). Earlier investigations of the litter layer close to our study plots confirmed these values. The litter C:N ratio of a *Q. petraea* dominated stand close to our HF plots was reported to be 63.2 and in a stand with *C. betulus* dominating in understory, close to the CS plots, 28.2 (Schume, 1992; Huber, 1993). As a consequence of rapid litter decomposition, CS might be privileged in terms of water balance particularly in the case of short precipitation events, since there is virtually no interception loss on the litter layer. No clear trend of SOC pools within a chronosequence was found, i.e. stand age had no significant influence on SOC stores. Between-plot variation is higher than any possible effect resulting from stand age, although chronosequence plots were selected carefully as suggested by Walker et al. (2010). Higher SOC pools in CS are attributed to the fertile soil type (chernozem). The difference of soil types becomes obvious when considering Fig. 4, where the plots of each management system are clearly separated. In CS, we found higher pore volumes and therefore lower bulk densities, resulting in better soil aeration and favourable water regime. Higher pH values promote the activity of soil organisms, resulting in elevated turnover rates. A higher share of species producing more easily decomposable litter (e.g. *C. betulus*) was found at CS sites, which also favours soil biological activity. SOC pools typically exhibit deferred reactions of low magnitude to silvicultural interventions, regardless of the intensity of harvest, and they are often only short-term (Johnson and Curtis, 2001). Management of logging residues, for instance, is more likely reflected in the biomass C pool for the next rotation, as is the case with SOC pools (Johnson et al., 2002). The share of the total carbon pool that is the SOC pool is nearly constant when comparing HF and CS, although significant differences in vegetation (structure, density, and species composition) and soil (eutric cambisol and haplic chernozem) are present. Hence, it seems that climatic factors, particularly temperature and precipitation, are main factors controlling carbon accumulation and its separation into different pools. This assumption is confirmed by Vande Walle et al. (2001), who also found such similarities between an oak–beech and an ash stand in Belgium. Substantial additional C sequestration in mineral soils is therefore not a simple task, specifically in broadleaved forest stands. A mixture of other broadleaved, particularly N-fixing species, could increase C mineralization as suggested by several studies (Johnson and Curtis, 2001; Huang et al., 2011).

4.1.2. Root C pools

The estimates for coarse root C pools reflect aboveground biomass C accumulation as they were estimated using allometric functions parameterized with aboveground stand parameters, while fine root biomass was actually measured. The ratio of fine root biomass to aboveground biomass was always higher in HF, probably due to more favourable soil conditions in CS. This is consistent with reports of increased fine root biomass production, for instance specifically under dry conditions (Santantonio and Hermann, 1985) or more generally where soil resources availability was low upslope (Noguchi et al., 2007). Slightly less than one quarter of the belowground C is stored in root biomass and this was found to be remarkably stable across our study plots which seem

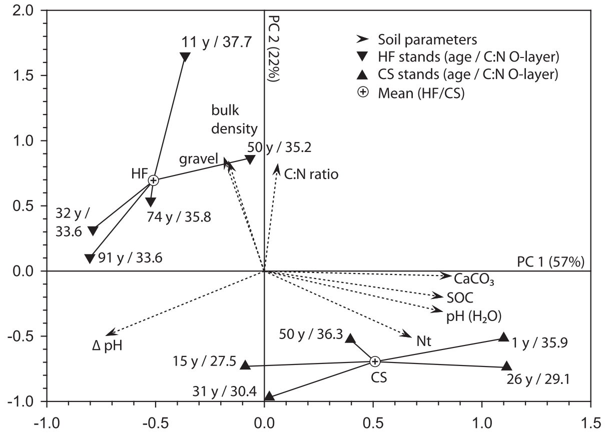

Fig. 4. Principal component analysis (PCA) ordination of the first two components showing the relationships between physical and chemical soil parameters: bulk density = ρ, gravel = gravel content (>2 mm), C:N ratio, $CaCO_3$ = carbonate content, SOC = soil organic carbon, pH (H_2O) = pH-value (H_2O), N_t = total nitrogen, ΔpH = (pH (H_2O) − pH ($CaCl_2$)). HF and CS chronosequence plots are shown with relation to their mean. PC = principal component.

to be again primarily controlled by climatic conditions. As a comparison, Djomo et al. (2011) recently reported a much higher proportion, 37%, in a moist tropical ecosystem (0–30 cm soil depth). Increased fine root production, in particular in topsoil horizons, was observed in a *Quercus ilex* forest following thinning operations with no disturbance of the root system (Lopez et al., 2003). According to this study, increased soil water and probably nutrient contents were the main drivers facilitating fine root growth after thinning. Certainly dense rooting woody and herbaceous understorey plants, emerging after harvests, contribute to increasing fine root biomass in the years following such silvicultural interventions. Fine root production followed a distinct pattern in both HF and CS, agreeing with earlier findings in chronosequence studies (Claus and George, 2005). While fine root biomass in HF increased after clearcut, reaching its maximum at 50 years and subsequently decreasing during stand maturation, a bimodal pattern was found in CS (Fig. 3). Fine root masses decreased, perhaps due to previous irregular standards removal at the 26 year old stand and increased rapidly thereafter. Again, total fine root biomass decreased as the stand entered the maturation phase. Late culmination of fine root biomass, as observed in HF, was previously reported in northern hardwood stands (Yanai et al., 2006). The obvious difference between the two chronosequence sets is the culmination point, which was reached earlier in CS (15 and 31 years) than in HF (50 years). Claus and George (2005) provide a possible explanation for this in which their data suggest that recovery of fine root biomass after a clearcut may take less time under favourable soil conditions, which is the case in CS (haplic chernozem) in contrast to HF (eutric cambisol). Our observation of root-to-shoot ratios for HF are consistent with previous studies e.g. Peri et al. (2010), who reported that the ratio in a *Northofagus* forest decreases with age until the stand reaches a steady-state asymptote beyond 60 years of age. Lower ratios in CS reflect more favourable soil conditions and thus reinforced aboveground C accumulation in comparison to HF, which was also in agreement with Peri et al. (2010).

4.2. N and C:N ratios

The history of both C and N accumulation is expressed by the C:N ratio, which is considered to be a measure for N availability. Soil C inputs originate from litter and fine root accumulation minus decomposition while the major sources of N inputs are litter, atmospheric deposition and biological N fixation through microorganisms. Depending on site conditions and N deposition rates, C:N ratios eventually increase with stand age as a consequence of higher C accumulation rates relative to N accumulation (Diochon et al., 2009). Conversely, opposite trends were observed in areas with high N deposition rates where N accumulation outpaced C accumulation leading to narrowing C:N ratios with increasing stand age (Goodale and Aber, 2001). C:N ratios in the O-layer were about $^1/_3$ wider than those observed in the adjacent mineral topsoil horizon (0–5 cm). Sampling was done at the end of the growing season and at that time the protein rich components of last year's litterfall were already consumed by soil organisms, leaving recalcitrant components (fruit capsules, branches) with a wider C:N ratio accumulated on the soil surface (O-layer). Narrower C:N ratios in deeper horizons suggest ongoing SOM humification and C oxidation, and subsequently relative accumulation of N-rich components. Narrow C:N values are typically associated with fine soil fractions in deeper horizons (Wiseman, 2003; Gerzabek et al., 2006). This is consistent with the present observation of increasing bulk density in deeper soil horizons (Table 2). We suggest that reduced competition for mineralized N in the older stands has facilitated N accumulation in the topsoil horizons and consequently narrowed C:N ratios in HF in accordance with the argumentation brought forward by Goodale and Aber (2001). As another mechanism involved, the present authors suppose increased heterotrophic microbial respiration as a consequence of canopy opening leads to higher rates of C respiration and N accumulation. In addition, low precipitation rates may minimize the amount of N leaching into deeper soil horizons which was previously shown even on sandy soils with N fertilization at comparable precipitation rates and short rotation willow coppice (SRWC) (Aronsson et al., 2000). Quite different dynamics were observed in CS, particularly in the O- and topsoil mineral horizon (0–5 cm) which could be explained by stand development patterns. Accumulation of woody logging residues on the forest floor such as branches and twigs, in addition to woody litter from standards, led to wider C:N ratios in the O-layer in the 1-year old stand. Consequent respiration of C-rich components and litter fall, as well as N deposition led to narrower C:N ratios after 15 years. As the canopy closes, competition for light causes decay of lower branches and twigs not exposed to sufficient amounts of light, leading to higher C accumulation rates relative to N accumulation. High N uptake rates during the rapid growth phase and aboveground biomass accumulation (Fig. 3), together with C accumulation rates result in steadily widening C:N ratios in the O-layer and topsoil mineral horizon. The assumption of increased N uptake during the rapid growth period is underpinned by the fact that C:N ratio is primarily controlled by N in CS, showing a negative correlation. Elevated N deposition rates as a consequence of the proximity to agricultural land might have an influence on C:N values and increase C mineralization in both study regions, as suggested by Mansson and Falkengren-Grerup (2003).

5. Conclusions for further research and forest management

(1) Ecosystem C pools are comparatively low throughout the study region, regardless of applied management strategies. Rapid decomposition and mineralization of litter, indicated by low O-horizon pools with wide C:N ratios at the end of a vegetation period, suggests high rates of litter C turnover and low rates of accumulation.
(2) Distinct C:N patterns in CS could be explained by stand phases via quantity and quality of litter inputs and changing demands of N during stand development.

(3) Climatic conditions, particularly temperature and precipitation, are main factors controlling carbon accumulation and its significance in different compartments.
(4) CS has higher net primary production (NPP), which is reflected by higher pools of C in aboveground biomass and coarse root pools.
(5) In our study, the chronosequence approach was not appropriate to resolve SOC temporal dynamics, but suitable to reveal dynamics of biomass stores and ratios (aboveground biomass, root biomass, root/shoot ratio) and C:N relationships in O-horizon and mineral soil.
(6) Fine root dynamics are generally in agreement with results of previously published papers, but we found a remarkable difference between the fine root mass culminating points in HF and CS.
(7) The impact of logging on SOC stores is low in both management systems and long-term trends were not observed.
(8) We assume that the warm and dry climate is a limiting factor in our study region; hence coppicing has the advantage of a fully functional root system after harvesting, facilitating rapid resprouting even under conditions of low rainfall and drying topsoil.

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References

Aronsson, P.G., Bergstrom, L.F., Elowson, S.N.E., 2000. Long-term influence of intensively cultured short-rotation Willow Coppice on nitrogen concentrations in groundwater. Journal of Environmental Management 58, 135–145.
Bellos, P., 2000. Biomasseuntersuchungen auf Mittelwald-Verjüngungsflächen (Unterholz). Diploma Thesis, Institute of Silviculture. University of Natural Resources and Life Sciences (BOKU), Vienna, 90p.
Bocock, K.L., 1964. Changes in the amounts of dry matter, nitrogen, carbon and energy in decomposing woodland leaf litter in relation to the activities of the soil fauna. J. Ecol. 52, 273–284.
Bolte, A., Ammer, C., Lof, M., Madsen, P., Nabuurs, G.J., Schall, P., Spathelf, P., Rock, J., 2009. Adaptive forest management in central Europe: climate change impacts, strategies and integrative concept. Scand. J. For. Res. 24, 473–482.
Bormann, F.H., Likens, G.E., 1979. Pattern and Process in a Forested Ecosystem Disturbance, Development and the Steady State Based on the Hubbard Brook Ecosystem Study. Springer, New York.
Chen, C.R., Xu, Z.H., 2005. Soil carbon and nitrogen pools and microbial properties in a 6-year-old slash pine plantation of subtropical Australia: impacts of harvest residue management. For. Ecol. Manage. 206, 237–247.
Claus, A., George, E., 2005. Effect of stand age on fine-root biomass and biomass distribution in three European forest chronosequences. Can. J. For. Res. 35, 1617–1625.
Conen, F., Zerva, A., Arrouays, D., Jolivet, C., Jarvis, P.G., Grace, J., Mencuccini, M., 2005. The carbon balance of forest soils: detectability of changes in soil carbon stocks in temperate and Boreal forests. SEB Exp. Biol. Ser. 2005, 235–249.
Cortez, J., 1998. Field decomposition of leaf litters: relationships between decomposition rates and soil moisture, soil temperature and earthworm activity. Soil Biol. Biochem. 30, 783–793.
De Vries, W., Reinds, G.J., Gundersen, P., Sterba, H., 2006. The impact of nitrogen deposition on carbon sequestration in European forests and forest soils. Global Change Biol. 12, 1151–1173.
De Vries, W., Soldberg, S., Dobbertin, M., Sterba, H., Laubhann, D., Van Oijen, M., Evans, C., Gundersen, P., Kros, J., Wamelink, G.W.W., Reinds, G.J., Sutton, M.A., 2009. The impact of nitrogen deposition on carbon sequestration by European forests and heathlands. For. Ecol. Manage. 258, 1814–1823.
Dickmann, D.I., 2006. Silviculture and biology of short-rotation woody crops in temperate regions: then and now. Biomass Bioenergy 30, 696–705.
Diochon, A., Kellman, L., Beltrami, H., 2009. Looking deeper: An investigation of soil carbon losses following harvesting from a managed northeastern red spruce (*Picea rubens* Sarg.) forest chronosequence. For. Ecol. Manage. 257, 413–420.
Djomo, A.N., Knohl, A., Gravenhorst, G., 2011. Estimations of total ecosystem carbon pools distribution and carbon biomass current annual increment of a moist tropical forest. For. Ecol. Manage. 261, 1448–1459.
Drexhage, M., Colin, F., 2001. Estimating root system biomass from breast-height diameters. Forestry 74, 491–497.
Englisch, M., 1992. Österreichische Waldboden-Zustandsinventur. Teil III: Atmogene Hauptnährstoffe. In: Österreichische Waldboden-Zustandsinventur. Ergebnisse. Forstliche Bundesversuchsanstalt, Vienna, 247p.
Foley, T.G., Richter, D.d., Galik, C.S., 2009. Extending rotation age for carbon sequestration: A cross-protocol comparison of North American forest offsets. For. Ecol. Manage. 259, 201–209.
Foster, B.L., Tilman, D., 2000. Dynamic and static views of succession: testing the descriptive power of the chronosequence approach. Plant Ecol. 146, 1–10.
Gaudinski, J.B., Trumbore, S.E., Davidson, E.A., Zheng, S.H., 2000. Soil carbon cycling in a temperate forest: radiocarbon-based estimates of residence times, sequestration rates and partitioning of fluxes. Biogeochemistry 51, 33–69.
Gerzabek, M.H., Antil, R.S., Kogel-Knabner, I., Knicker, H., Kirchmann, H., Haberhauer, G., 2006. How are soil use and management reflected by soil organic matter characteristics: a spectroscopic approach. Eur. J. Soil Sci. 57, 485–494.
Giardina, C.P., Ryan, M.G., Hubbard, R.M., Binkley, D., 2001. Tree species and soil textural controls on carbon and nitrogen mineralization rates. Soil Sci. Soc. Am. J. 65, 1272–1279.
Glück, S., 1996. Biomasseuntersuchungen auf einer Eichenversuchsfläche des nordöstlichen Niederösterreich unter Zuhilfenahme statistischer Methoden. Diploma Thesis, Institute of Forest Ecology. University of Natural Resources and Life Sciences, Vienna, 84p.
Goodale, C.L., Aber, J.D., 2001. The long-term effects of land-use history on nitrogen cycling in northern hardwood forests. Ecol. Appl. 11, 253–267.
Hart, S.C., Selmants, P.C., Boyle, S.I., Overby, S.T., 2006. Carbon and nitrogen cycling in southwestern ponderosa pine forests. For. Sci. 52, 683–693.
Hochbichler, E., 1993. Methods of oak silviculture in Austria. Ann. For. Sci. 50, 583–591.
Hochbichler, E., 2002. Vorläufige Ergebnisse von Biomasseninventuren in Buchen- und Mittelwaldbeständen. In: Dietrich, H.-P., Raspe, S., Preuhsler, T. (Eds.), Inventur von Biomasse- und Nährstoffvorräten in Waldbeständen. LWF, München, pp. 37–46.
Hochbichler, E., 2008. Fallstudien zur Struktur, Produktion und Bewirtschaftung von Mittelwäldern im Osten Österreichs (Weinviertel). Österr. Ges. für Waldökosystemforschung und Experimentelle Baumforschung Univ. für Bodenkultur, Wien.
Hochbichler, E., Bellos, P., Lick, E., 2006. Biomass functions for estimating needle and branch biomass of spruce (*Picea Abies*) and Scots pine (*Pinus Sylvestries*) and branch biomass of beech (*Fagus sylvatica*) and oak (*Quercus robur* and *petrea*). Aust. J. For. Sci. 123, 35–46.
Hochbichler, E., Bruckman, V.J., Spinka, S., Glatzel, G., Grieshofer, H., 2009. Untersuchungen zur Dynamik der Biomassen- und Kohlenstoffvorräte in Niederwäldern mit Überhälter, Mittel- und Hochwäldern. DaFNE Research Reports. University of Natural Resources and Life Sciences, Department for Forest and Soil sciences, Vienna, 154p.
Hochbichler, E., Putzgruber, N., 2004. Biomassenschätzfunktionen für Wurzeln von Esche, Bergahorn, Robinie und Hasel aus Mittelwäldern. Unpublished Report. University of Natural Resources and Life Sciences, Department for Forest and Soil sciences, Vienna.
Hochbichler, E., Putzgruber, N., Krapfenbauer, A., 1994. Biomassen- und Nährstoffuntersuchungen in einem 40-jährigen Buchenbestand (*Fagus sylvatica* L.). Aust. J. For. Sci. 111, 1–22.
Hopmans, P., Bauhus, J., Khanna, P., Weston, C., 2005. Carbon and nitrogen in forest soils: potential indicators for sustainable management of eucalypt forests in south-eastern Australia. For. Ecol. Manage. 220, 75–87.
Huang, Y.-H., Li, Y.-L., Xiao, Y., Wenigmann, K.O., Zhou, G.-Y., Zhang, D.-Q., Wenigmann, M., Tang, X.-L., Liu, J.-X., 2011. Controls of litter quality on the carbon sink in soils through partitioning the products of decomposing litter in a forest succession series in South China. For. Ecol. Manage. 261, 1170–1177.
Huber, S., 1993. Bodenmineralstoffhaushalt, Ernährungszustand und Kronenverlichtung von Eichenwäldern im nordöstlichen Österreich. In: FIW – Forschungsberichte 1993/3.
IUSS Working Group WRB, 2006. World reference bases for soil resources 2006. World Soil Resources Reports No. 103. FAO, Rome.
Jacob, M., Viedenz, K., Polle, A., Thomas, F.M., 2010. Leaf litter decomposition in temperate deciduous forest stands with a decreasing fraction of beech (*Fagus sylvatica*). Oecologia 164, 1083–1094.
Jakucs, P., 1985. Higher plants. In: Jakucs, P. (Ed.), Ecology of an oak forest in Hungary – Results of "Sikfökut Project". Akademiai Kiado, Budapest.
Johnson, D.W., Curtis, P.S., 2001. Effects of forest management on soil C and N storage: meta analysis. For. Ecol. Manage. 140, 227–238.
Johnson, D.W., Knoepp, J.D., Swank, W.T., Shan, J., Morris, L.A., Van Lear, D.H., Kapeluck, P.R., 2002. Effects of forest management on soil carbon: results of some long-term resampling studies. Environ Pollut 116, 201–208.
Kulmatiski, A., Vogt, D.J., Siccama, T.G., Beard, K.H., 2003. Detecting nutrient pool changes in rocky forest soils. Soil Sci. Soc. Am. J. 67, 1282–1286.
Lal, R., 2005. Forest soils and carbon sequestration. For. Ecol. Manage. 220, 242–258.

Lamlom, S.H., Savidge, R.A., 2003. A reassessment of carbon content in wood: variation within and between 41 North American species. Biomass Bioenergy 25, 381–388.
Laschober, A., 2000. Waldbauliche Untersuchungen zur Verjüngungs- und Jungwuchsentwicklung auf Mittelwaldstandorten. Diploma Thesis, Department of Forest- and Soil Sciences. University of Natural Resources and Life Sciences, Vienna, 100p.
Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolstrom, M., Lexer, M.J., Marchetti, M., 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For. Ecol. Manage. 259, 698–709.
Liski, J., Perruchoud, D., Karjalainen, T., 2002. Increasing carbon stocks in the forest soils of western Europe. For. Ecol. Manage. 169, 159–175.
Lopez, B.C., Sabate, S., Gracia, C.A., 2003. Thinning effects on carbon allocation to fine roots in a *Quercus ilex* forest. Tree Physiol. 23, 1217–1224.
Ma, X.Q., Heal, K.V., Liu, A.Q., Jarvis, P.G., 2007. Nutrient cycling and distribution in different-aged plantations of Chinese fir in southern China. For. Ecol. Manage. 243, 61–74.
Mansson, K.F., Falkengren-Grerup, U., 2003. The effect of nitrogen deposition on nitrification, carbon and nitrogen mineralisation and litter C:N ratios in oak (*Quercus robur* L.) forests. For. Ecol. Manage. 179, 455–467.
Muneer, M., Oades, J.M., 1989. The role of Ca–organic interactions in soil aggregate stability. III. Mechanisms and models. Aust. J. Soil Res. 27, 411–423.
Nabuurs, G.J., Thurig, E., Heidema, N., Armolaitis, K., Biber, P., Cienciala, E., Kaufmann, E., Makipaa, R., Nilsen, P., Petritsch, R., Pristova, T., Rock, J., Schelhaas, M.J., Sievanen, R., Somogyi, Z., Vallet, P., 2008. Hotspots of the European forests carbon cycle. For. Ecol. Manage. 256, 194–200.
Nilsen, P., Strand, L.T., 2008. Thinning intensity effects on carbon and nitrogen stores and fluxes in a Norway spruce (*Picea abies* (L.) Karst.) stand after 33 years. For. Ecol. Manage. 256, 201–208.
Noguchi, K., Konopka, B., Satomura, T., Kaneko, S., Takahashi, M., 2007. Biomass and production of fine roots in Japanese forests. J. For. Res. – Jpn 12, 83–95.
Nyland, R.D., 2002. Silviculture: Concepts and Applications. McGraw-Hill, New York.
Offenthaler, I., Hochbichler, E., 2006. Estimation of root biomass of Austrian forest tree species. Aust. J. For. Sci. 123, 65–86.
ON L 1080-99, 1999. Chemical analyses of soils – determination of organic carbon by dry combustion. In: ÖNORM L 1080. Austrian Standards Institute, Vienna.
ON L 1082-99, 1999. Chemical analyses of soils – determination of nitrogen according to Kjeldahl. In: ÖNORM L 1082. Austrian Standards Institute, Vienna.
ON L 1083-99, 1999. Chemical analyses of soils – determination of acidity (pH-value). In: ÖNORM L 1083. Austrian Standards Institute, Vienna.
ON L 1084-99, 1999. Chemical analyses of soils – determination of carbonate. In: ÖNORM L 1084. Austrian Standards Institute, Vienna.
Pellinen, P., 1986. Biomasseuntersuchungen im Kalkbuchenwald. Dissertation, Faculty of Forestry, Göttingen University, Göttingen, 145p.
Peri, P.L., Gargaglione, V., Martínez Pastur, G., Vanesa Lencinas, M., 2010. Carbon accumulation along a stand development sequence of *Nothofagus antarctica* forests across a gradient in site quality in Southern Patagonia. For. Ecol. Manage. 260, 229–237.
Pertlik, E., 1982. Verhältnis der Masse der Mistel (*Loranthus europaeus*) zur Masse der Eiche (*Quercus* sp.) und Vergleich der Gehalte N, P, K, Ca und Mg in der Trockenmasse. Diploma Thesis, Department of Forest- and Soil Sciences. University of Natural Resources and Life Sciences, Vienna, 71p.
Pickett, S.T.A., 1989. Space-for-time substitutions as an alternative to long-term studies. In: Likens, G.E. (Ed.), Long-term Studies in Ecology. Springer, New York, pp. 110–135.
Santantonio, D., Hermann, R.K., 1985. Standing crop, production, and turnover of fine roots on dry, moderate, and wet sites of mature Douglas-fir in western Oregon. Ann. For. Sci. 42, 113–142.
Schume, H., 1992. Vegetations- und standortkundliche Untersuchungen in Eichenwäldern des nordöstlichen Niederösterreich unter Zuhilfenahme multivariater Methoden. FIW – Forschungsberichte 1992/3.
Seidl, R., Rammer, W., Jager, D., Currie, W.S., Lexer, M.J., 2007. Assessing trade-offs between carbon sequestration and timber production within a framework of multi-purpose forestry in Austria. For. Ecol. Manage. 248, 64–79.
Smidt, S., 2007. 10 Jahre Depositionsmessung im Rahmen des europäischen Waldschadensmonitorings-Ergebnisse 1996–2005; FDK 181.45:(436). BFW – Bundesforschungs- und Ausbildungszentrum für Wald Naturgefahren und Landschaft, Wien.
Van Hees, A.F.M., Clerkx, A.P.P.M., 2003. Shading and root-shoot relations in saplings of silver birch, pedunculate oak and beech. For. Ecol. Manage. 176, 439–448.
Van Miegroet, H., Moore, P.T., Tewksbury, C.E., Nicholas, N.S., 2007. Carbon sources and sinks in high-elevation spruce-fir forests of the Southeastern US. For. Ecol. Manage. 238, 249–260.
Vande Walle, I., Mussche, S., Samson, R., Lust, N., Lemeur, R., 2001. The above- and belowground carbon pools of two mixed deciduous forest stands located in East-Flanders (Belgium). Ann. For. Sci. 58, 507–517.
Vesterdal, L., Schmidt, I.K., Callesen, I., Nilsson, L.O., Gundersen, P., 2008. Carbon and nitrogen in forest floor and mineral soil under six common European tree species. For. Ecol. Manage. 255, 35–48.
Walker, L.R., Wardle, D.A., Bardgett, R.D., Clarkson, B.D., 2010. The use of chronosequences in studies of ecological succession and soil development. J. Ecol. 98, 725–736.
Watanabe, Y., Masunaga, T., Owusu-Sekyere, E., Moro Buri, M., Idowu Oladele, O., Wakatsuki, T., 2009. Evaluation of growth and carbon storage as influenced by soil chemical properties and moisture on teak (*Tectona grandis*) in Ashanti region, Ghana. J. Food Agric. Environ. 7, 640–645.
Wiseman, C.L.S., 2003. Organic carbon sequestration in soils: an investigation of five profiles in Hesse, Germany. In: Fachbereich Geowissenschaften/Geographie. Johann Wolfgang Goethe – Universität, Frankfurt am Main, 268p.
Yanai, R.D., Park, B.B., Hamburg, S.P., 2006. The vertical and horizontal distribution of roots in northern hardwood stands of varying age. Can J Forest Res 36, 450–459.
Zhang, D.Q., Hui, D.F., Luo, Y.Q., Zhou, G.Y., 2008. Rates of litter decomposition in terrestrial ecosystems: global patterns and controlling factors. J. Plant Ecol. – UK 1, 85–93.

Scientific publications

Paper 2

Paper 2: Improved soil carbonate determination by FT-IR and X-ray analysis

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Abstract

In forest soils on calcareous parent material, carbonate is a key component that influences both chemical and physical soil properties and thus fertility and productivity. At low organic carbon contents, it is difficult to distinguish between organic and inorganic carbon (carbonate) in soils. The common gas-volumetric method to determine carbonate has a number of disadvantages. We hypothesize that a combination of two spectroscopic methods, which account for different forms of carbonate, can be used to model soil carbonate in our study region. Fourier transform mid-infrared spectroscopy was combined with X-ray diffraction to develop a model based on partial least squares regression. Results of the gas-volumetric Scheibler method were corrected for the calcite/dolomite ratio. The best model performance was achieved when we combined the two analytical methods using four principal components. The root mean squared error of prediction decreased from 13.07 to 11.57, while full cross-validation explained 94.5% of the variance of the carbonate content. This is the first time that a combination of the proposed methods has been used to predict carbonate in forest soils, offering a simple method to precisely estimate soil carbonate contents while increasing accuracy in comparison with spectroscopic approaches proposed earlier. This approach has the potential to complement or substitute gas-volumetric methods, specifically in study areas with low soil heterogeneity and similar parent material or in long-term monitoring by consecutive sampling.

Keywords: Forest soil, Carbonate, Fourier transform mid-infrared spectroscopy, X-ray diffraction, Partial least squares regression, Scheibler method

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ORIGINAL PAPER

Improved soil carbonate determination by FT-IR and X-ray analysis

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Abstract In forest soils on calcareous parent material, carbonate is a key component that influences both chemical and physical soil properties and thus fertility and productivity. At low organic carbon contents, it is difficult to distinguish between organic and inorganic carbon, e.g. carbonates, in soils. The common gas-volumetric method to determine carbonate has a number of disadvantages. We hypothesize that a combination of two spectroscopic methods, which account for different forms of carbonate, can be used to model soil carbonate in our region. Fourier transform mid-infrared spectroscopy was combined with X-ray diffraction to develop a model based on partial least squares regression. Results of the gas-volumetric Scheibler method were corrected for the calcite/dolomite ratio. The best model performance was achieved when we combined the two analytical methods using four principal components. The root mean squared error of prediction decreased from 13.07 to 11.57, while full cross-validation explained 94.5 % of the variance of the carbonate content. This is the first time that a combination of the proposed methods has been used to predict carbonate in forest soils, offering a simple method to precisely estimate soil carbonate contents while increasing accuracy in comparison with spectroscopic approaches proposed earlier. This approach has the potential to complement or substitute gas-volumetric methods, specifically in study areas with low soil heterogeneity and similar parent material or in long-term monitoring by consecutive sampling.

Keywords Forest soil · Carbonate · Fourier transform mid-infrared spectroscopy · X-ray diffraction · Partial least squares regression · Scheibler method

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Introduction

Carbonate is a key component of soils on calcareous parent material, influencing both chemical and physical soil properties and hence fertility and productivity. It directly affects the soil pH and buffer capacity and is in strong reciprocation with biochemical cycles. Carbonate promotes the formation of stable soil aggregates and influences physical soil properties such as hydraulic characteristics and erodibility. It typically occurs as calcite ($CaCO_3$) and/or dolomite ($CaMg[CO_3]_2$), depending on the parent material and soil formation processes. A number of different methods of carbonate determination in soils were proposed over the last decades, principally based on approaches in which released CO_2 gas is directly measured either volumetrically or gravimetrically as a consequence of mass loss after treatment with acids. Other approaches are spectroscopic by means of Fourier transform infrared (FT-IR) or Raman spectroscopy or X-ray diffractometry (XRD) (Gunasekaran et al. 2006). A good overview of common methods is presented in Kamogawa et al. (2001). The gas-volumetric Scheibler method (ON L 1084-99, 1999) is still widely used, despite its weaknesses, for example, analytical precision, time consumption, and varying reaction times based on the present type of carbonates. Low solubility of dolomite in 10 % HCl leads to

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longer reaction times as compared to calcite (Schlichting et al. 1995), and consequently, total carbonate might be underestimated or organic carbon might be overestimated (after subtraction of inorganic carbon from total carbon). FT-IR spectroscopy, on the other hand, has proven to have the potential for accurate quantitative estimations (Janik and Skjemstad 1995; Tatzber et al. 2007, 2011; Ji et al. 2009). The current study aims at developing a model for carbonate quantification using a combination of FT-IR spectroscopy and XRD. Reference material is forest soil from a series of recently established long-term observation plots for studying woody biomass production. A similar approach was recently used in aquatic ecosystems for the identification of Heinrich events in marine deposits (Ji et al. 2009). We hypothesize that the determination of the form of carbonate actually occurring on our plots (calcite, dolomite) would increase the accuracy of predicting carbonate contents in our model.

Experimental

Soil sampling and preparation

The soil samples were collected in Eastern Austria, in a *Quercus* dominated high forest management system. The parent material consists of gravel, sand and silt built up during the Pannonium as a result of the early development of the Danube River. Parts of the deposited material originate from the northern limestone Alps, therefore containing considerable amounts of carbonate. Younger Aeolian deposits of loess (Pleistocene) from the same source region led to periglacial formation of Chernozems. A detailed site description and soil characterization as well as belowground organic carbon dynamics can be found in Bruckman et al. (2011). Only soils that obviously contained carbonates (determined by a pH [$CaCl_2$] value > 6 (Cools and de Vos 2010)), which is the case for approximately 10 % of all samples, were selected for this study. As a consequence of the geological background and diverse parent material, both calcite and dolomite are present in the soil matrix. Three soil reference groups were identified according to WRB (IUSS Working Group WRB 2006) across our study region, where five plots are classified as Cambisols, three as Luvisols and one as Chernozem. Mineral soil cores were divided into five geometric horizons, 0–5, 5–10, 10–20, 20–40 and 40–50 cm soil depth, and were analysed separately. Soil samples were sieved to 2 mm, and a subsample was ground to powder for Fourier transform mid-infrared (FT-MIR) and XRD analysis.

Gas-volumetric Scheibler method

The gas-volumetric determination of carbonate (Scheibler method) was conducted following ÖN L 1084-99 (1999), also described in Tatzber et al. (2007). Carbonate contents calculated from the Scheibler method were corrected for the dolomite content of the respective samples using a stoichiometric coefficient based on the calcite/dolomite XRD peak area ratios. Ambient air pressure and temperature were recorded for each sample in order to calculate the pT coefficient, which corrects the volume of CO_2 for current temperature and air pressure during the reaction. The reaction time was extended in order to allow complete dissolution of dolomite in the samples.

Fourier transform mid-infrared spectroscopy

KBr pellets were produced to measure samples in transmission mode in the mid-infrared area, that is, 400–4,000 cm^{-1}, using a Bruker Optics Tensor 27 spectrometer. Approximately 1 mg bulk soil sample, which was dried at 70 °C for at least 12 h prior to measurement, was mixed with 200 mg FT-IR grade KBr (both weighed exactly) and ground in an agate grinding mill. The mixed bulk soil and KBr powder was immediately pressed to obtain a transparent pellet and measured. According to our observation, it is crucial to store KBr and all manipulation tools such as press chambers and cylinders at 70 °C as this promotes sintering during pressing and results in completely transparent pellets of high quality. Sixteen scans were performed for each sample and averaged. The spectra were corrected against a pure KBr pellet and ambient air. A background spectrum was measured at least every 30 min. All spectra were baseline corrected before conducting further analysis. According to Beer's law, the magnitude of a signal is proportional to the concentration of the respective component causing IR absorption at its specific wavelength, allowing quantitative conclusions. For this reason, absorption spectra were used for analysis, rather than transmission spectra that are shown in Fig. 1. Six indicative peak regions were selected for integration with base points at 2,686 and 2,460 cm^{-1} (Peak I), 1,850 and 1,784 cm^{-1} (Peak II), 1,567 and 1,295 cm^{-1} (Peak III), 889 and 867 cm^{-1} (Peak IV), 734 and 719 cm^{-1} (Peak V), and 719–708 cm^{-1} (Peak VI). Location of peaks was derived from Ji et al. (2009) and Tatzber et al. (2010). While peaks I–IV represent a combination of calcite and dolomite, which is not clearly separable, V is indicative of dolomite and VI of calcite. The exact location of the peaks and base points was set according to our own results; hence, they are not necessarily convergent to the cited papers.

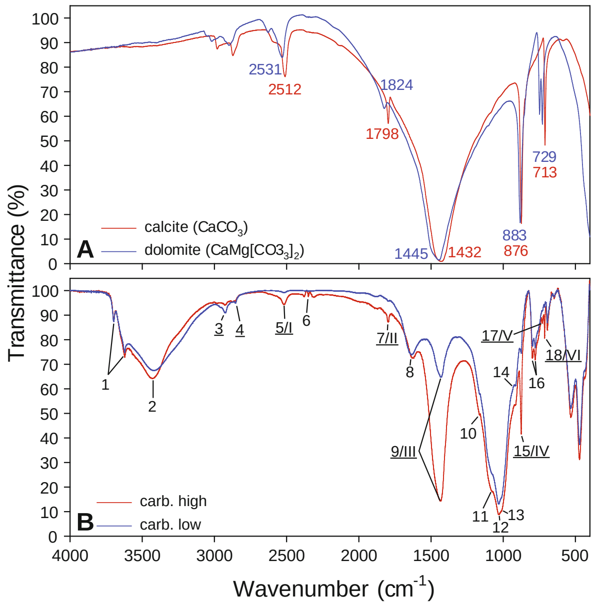

Fig. 1 Pure carbonate and bulk soil infrared spectra. **A** Mid-infrared (MIR) range spectrum of pure calcite ($CaCO_3$) and dolomite ($CaMg[CO_3]_2$). Calcite and dolomite peaks used in this study are indicated by their respective wavenumber. **B** MIR spectra of bulk soil samples with the lowest (carb. low) and the highest (carb. high) carbonate concentrations of all samples. Carb. high: 19.6 % carbonate by weight, 40–50 cm soil depth, calcite/dolomite ratio = 1.52, Chernozem. Carb. low: 0.5 % carbonate by weight, 0–5 cm soil depth, calcite/dolomite ratio = 0.92, Chernozem. Peaks are indicated for most important infrared-active functional groups occurring in mineral soils (Tatzber et al. 2010). Indicative peaks for carbonate are *underlined,* and *Roman numbers* represent peaks used in our model. 1 = Si–O–H vibrations of layer silicates; 2 = O–H (H bonded), N–H; 3 = asymmetrical CH_2 stretching, carbonate; 4 = symmetrical CH_2 stretching, carbonate; 5 = carbonate; 6 = ambient CO_2; 7 = carbonate (calcite dominated); 8 = C–O stretch (carboxylates, aromatic vibrations), O–H bending of water; 9 = carbonate, carboxylates; 10 = C–O stretch of OH deformation of COOH; 11 = Si–O–Si, sulphate; 12 = C–O stretch, carbohydrates; 13 = SiO_3^{2-}, CH vibrations; 14 = C–H deformation of aromatics, cyclopentane; 15 = carbonate; 16 = quartz; 17 = dolomite; 18 = calcite

Powder X-ray diffraction

Powder XRD was performed with ground bulk soil samples using a PANalytical X'pert Pro Diffractometer with CuKα radiation at a tension of 45 kV, and a current of 40 mA. Scanning was performed from 5° to 70°2θ at an interval of 0.017°, with a measuring time of 25 s per step. X-Ray diffraction allows a distinct differentiation between calcite and dolomite and calculation of respective ratios, which could be used to raise accuracy of carbonate determination. Approximately two grams of ground sample material is needed, which can be recycled and used for further analysis since the measurement is non-destructive. Sample preparation is simple and measurement is relatively fast if newer instrumentation is used (~15 min per sample) and no additional consumables are needed. However, the main limitations are its detection limit which is around 1 % by weight and relatively high investment costs for the analytical equipment (Ji et al. 2009). Two indicative peaks were selected for integration, representing calcite at 29.5°2θ (Peak VII) and dolomite at 31°2θ (Ji et al. 2009). Base points were set individually for each sample, representing local minima before and after the peak location.

Partial least squares regression

Partial least squares regression (PLSR) was used to develop a model for carbonate estimation at our study site. PLSR is among the most commonly used procedures for spectral chemometrics, which is also confirmed in the comprehensive review by Rossel et al. (2006). The first step is a reduction in dimensions. Principal components are computed from the predictor values, which are used to predict scores of the dependent values' components. Subsequently, the scores are used to compute the actual dependent values. Advantages of this method are its relative robustness with respect to missing data and noise and its ability to handle multicollinearity among the independent input values. The statistical software R (R Development Core Team 2011) in combination with the PLS package (Mevik and Wehrens 2007) was used to develop our model.

Results and discussion

Results obtained by the Scheibler method

Using the Scheibler method, we found a mean carbonate content of 5.4 % by weight, ranging from 0.5 to 19.6 %, which represents contents of 4.6–196.4 mg g^{-1}. The mean calcite/dolomite ratio, based on the integrated XRD bands VII and VIII, was 1.18, when excluding four samples with low dolomite contents which present an elevated mean ratio of 41.67. The four samples were from the plot where the soil was identified as Cambisol. In situ observations during soil sampling showed clear signs of secondary carbonates, that is, carbonates that are formed by biological processes at these rather dry sites and consist of calcite. Earthworm-secreted carbonate could be a significant component of biogeochemical C and Ca cycling (Lambkin et al. 2011). Based on this observation, grinding the soil samples for analysis is strongly suggested after sieving (2 mm).

Combination of Fourier transform mid-infrared and X-ray diffraction results

Pure calcite and dolomite spectra are shown in Fig. 1A. Bands appeared at 2,984, 2,873, 2,512, 1,798, 1,432 cm^{-1} (ν_3), 876 cm^{-1} (ν_2), and 713 cm^{-1} (ν_4). Tatzber et al. (2007) produced very similar results on pure calcite, using a different instrument (Perkin Elmer Paragon 500 Spectrometer), and a detailed description of the underlying functional groups of the respective bands can be found in their study. It seems that dolomite peaks appear at shorter wavelengths, with a mean difference of 21.4 ± 11.1 cm^{-1} in comparison with calcite. Respective dolomite bands appeared at 3,024, 2,902, 2,531, 1,824, and 1,445 cm^{-1} (ν_3), 883 cm^{-1} (ν_2), and 729 cm^{-1} (ν_4). This comparison reveals potential difficulties in setting appropriate base points when integrating bands of bulk soil samples since carbonate typically occurs in different relative amounts of calcite and dolomite (sometimes also other carbonates, e.g. siderite) in soils. As a consequence, bands of bulk soil samples (Fig. 1B) are less distinctive and usually broader as compared to pure carbonate spectra and in some cases overlapped by other non-calcareous constituents. This, for instance, in the 3,024–2,873 cm^{-1} band area, which is overlapped by aliphatic groups, causes CH_2 stretching signals. Hence, this area was excluded for carbonate determination based on FT-MIR spectroscopy. We selected an integration mode where the integrated peak area (corrected for the amount of sample) is delimited by the peak itself within the base points and a straight line between them. Integration up to the x-axis showed weaker model performances, which was most likely caused by slightly different amounts of sample in each pellet.

While most bands appear in the same magnitude at a given amount of sample, some bands tend to show weaker signals in case of dolomite, which is especially true for the 1,824 cm^{-1}/II band. If only this band is considered for predictive calculations and treated as a common carbonate band, one might underestimate carbonate if the soil contains considerable amounts of dolomite.

X-ray diffractograms (Fig. 2) reveal a distinct pattern of mineral soil samples, with clear indicators of considerable amounts of clay minerals (e.g. chlorites) in general and to some extent, more specific details of other types of layer silicates. Being one of the fractions most resistant against chemical weathering in soils, quartz represents the most dominant peaks at 20.9°2θ and 26.6°2θ. Calcite (at 29.5°2θ/VII) and dolomite (at 31°2θ/VIII) are well separated and clearly no overlap occurs, making it comparatively simple to set base points for peak area integration and to determine the calcite/dolomite ratio to improve the Scheibler results. Using this approach, our results were corrected by up to 3.8 %, while the mean correction factor was 0.1 %, depending on the calcite/dolomite ratio and the pT factor during Scheibler measurement.

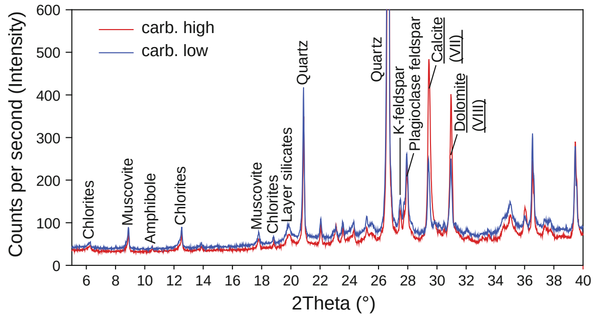

Fig. 2 X-ray diffractogram of the same carb. high and carb. low bulk soil samples as shown in Fig. 1B. The most important peaks to characterize the soil are indicated. Note the distinct separation of calcite and dolomite

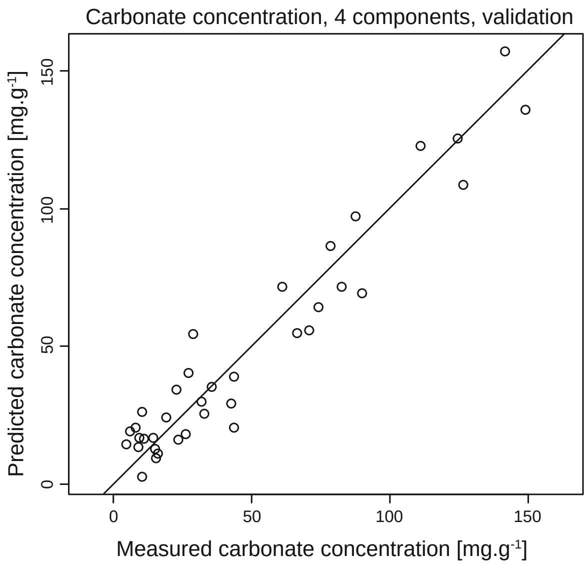

Fig. 3 Cross-validated predictions for carbonate contents derived by Scheibler method, corrected for calcite/dolomite ratios. The lowest root mean squared error of prediction (RMSEP (r^2_{CV}) = 11.57) (adj. CV) was derived with a model including four principal components and XRD calcite and dolomite peaks in combination with improved Scheibler carbonate estimates. Cross-validation training explained 100 % of the variance of predictors and 94.5 % of the variance of the dependent (carbonate concentration)

Figure 3 shows the results of the carbonate prediction model including mid-infrared bands and the calcite and dolomite peaks from XRD as predictors and corrected Scheibler carbonate concentrations as the dependent variable; 94.65 % variance of the predictors was explained, employing a model that embraces four principal components. Including more components leads to a higher root mean squared error of prediction and hence a poorer model performance as a consequence of increased model complexity. Our model represents the data set satisfactory, and both inclusions of bands VII and VIII from XRD and the improved Scheibler estimates (stoichiometric coefficient) enhanced overall performance. As a result, the root mean squared error of prediction decreased from 13.07 to 11.57. The improvement was pronounced in samples with higher carbonate contents >100 mg g^{-1}. However, we had to exclude one sample with the highest carbonate content (196.4 mg g^{-1}) from our model calculation as it turned out to be an outlier.

Interpretation of main model components

Calcite and dolomite represent the first two main components, and a loading plot is shown in Fig. 4. While bands I–IV, VI, and VII are indicative of calcite or calcite and dolomite and load predominantly on Component 1, bands V and VIII represent dolomite and predominantly load on Component 2. Depicted positions of soil horizons with their respective pH value in aqueous solution clearly show the trend of increasing carbonate contents and pH values with increasing soil depth. However, it seems that calcite is the main determinant of this observation, which could be explained by its relatively better solubility in weak acids, such as precipitation and humic acids in soil solution as compared to dolomite; hence, it is preferably translocated into deeper soil horizons in forest soils. This illustrates the importance of considering soil inorganic carbon as a combination of different forms of carbonate, influencing soil chemical processes, and utilizing quantitative spectroscopic approaches, and examples from previous research

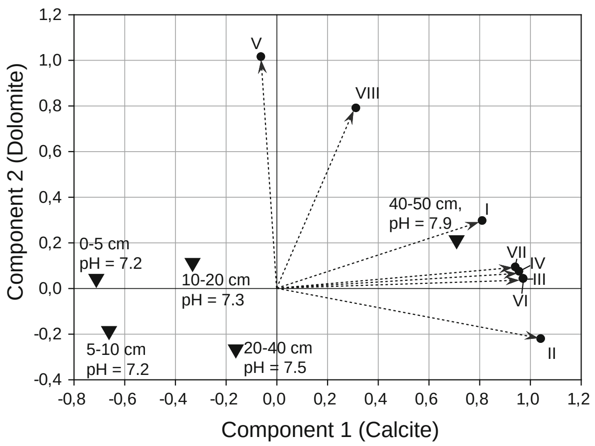

Fig. 4 Results of a principal component analysis (PCA) with oblique rotation at KMO = 0.877 and Bartlett's test of sphericity χ^2 (28) = 755.84; $p < 0.001$. Component loadings of mid-infrared and XRD bands are shown (*black dots*, see Experimental section for band assignments and wavelength information) together with genetic soil horizons (*triangles*) and their respective pH value (H_2O)

in marine sediments (Ji et al. 2009) underline this proclamation.

Conclusion

For the samples in our study from three different soil reference groups, the model shows a good performance in predicting carbonate contents across the study region. The proposed method can be used as an alternative approach for estimating carbonate content in soils. Here, we show that PLSR is a suitable method, even if the sample size is small, and that the model performance is increased by including information on the actual occurring forms of carbonate, for example, bands V and VII as a proxy for dolomite. As compared to other published spectroscopic approaches, based typically on a single method, a combination of methods has the potential to improve accuracy. However, we suggest a larger study, based on more samples from different soils and vegetation types to validate our results. Samples with high carbonate contents (>15 %) should be included to test the stability of the proposed method at high concentration levels.

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References

Bruckman VJ, Yan S, Hochbichler E, Glatzel G (2011) Carbon pools and temporal dynamics along a rotation period in *Quercus* dominated high forest and coppice with standards stands. For Ecol Manag 262:1853–1862

Cools N, de Vos B (2010) Sampling and analysis of soil. Manual part X. In: Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. UNECE, ICP Forests, Hamburg

Gunasekaran S, Anbalagan G, Pandi S (2006) Raman and infrared spectra of carbonates of calcite structure. J Raman Spectrosc 37:892–899

IUSS Working Group WRB (2006) World reference bases for soil resources 2006. World soil resources reports no. 103. Food and Agricultural Organization of the United Nations FAO, Rome

Janik LJ, Skjemstad JO (1995) Characterization and analysis of soils using mid-infrared partial least-squares. II.*Correlations with some laboratory data. Aust J Soil Res 33:637–650

Ji JF, Ge Y, Balsam W, Damuth JE, Chen J (2009) Rapid identification of dolomite using a fourier transform infrared spectrophotometer (FTIR): a fast method for identifying Heinrich events in IODP Site U1308. Mar Geol 258:60–68

Kamogawa MY, Nogueira ARA, Miyazawa M, Artigas J, Alonso J (2001) Determination of soil calcareous efficiency using flow system with pervaporative separation. Anal Chim Acta 438:273–279

Lambkin DC, Canti MG, Piearce TG, Hodson ME (2011) Dissolution rates of earthworm-secreted calcium carbonate. Appl Geochem 26(Suppl):67–69

Mevik BH, Wehrens R (2007) The pls package: principal component and partial least squares regression in R. J Stat Softw 18:1–24

ON L 1084-99 (1999) Chemical analyses of soils—determination of carbonate. In: Austrian Standards Institute (ed) ÖNORM L 1084. Austrian Standards Institute, Vienna

R Development Core Team (2011) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

Rossel RAV, Walvoort DJJ, McBratney AB, Janik LJ, Skjemstad JO (2006) Visible, near infrared, mid infrared or combined diffuse reflectance spectroscopy for simultaneous assessment of various soil properties. Geoderma 131:59–75

Schlichting E, Blume HP, Stahr K (1995) Bodenkundliches Praktikum—eine Einführung in pedologisches Arbeiten für Ökologen, insbesondere Land- und Forstwirte, und für Geowissenschaftler. Blackwell Wiss.-Verl., Berlin; Wien u.a.

Tatzber M, Stemmer M, Spiegel H, Katzlberger C, Haberhauer G, Gerzabek M (2007) An alternative method to measure carbonate in soils by FT-IR spectroscopy. Environ Chem Lett 5:9–12

Tatzber M, Mutsch F, Mentler A, Leitgeb E, Englisch M, Gerzabek MH (2010) Determination of organic and inorganic carbon in forest soil samples by mid-infrared spectroscopy and partial least squares regression. Appl Spectrosc 64:1167–1175

Tatzber M, Mutsch F, Leitgeb E, Englisch M, Mentler A, Gerzabek M (2011) Mid-infrared spectroscopy for determinations of carbonate in soils-what is important? Am Lab 43:13–17

Selected contributions at international scientific events

Geophysical Research Abstracts
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EGU General Assembly 2010

Determinants of soil organic carbon pools in oak stands in northeastern Austria

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Recently deciduous forests in northeastern Austria received increased attention as potential sources of biomass for energetic utilisation. There are still substantial deficits in the knowledge on carbon pools, -sequestration and -dynamics at these forest sites. The aim of our study was therefore to identify the main determinants which control soil organic carbon (SOC) pools in differently managed Quercus petraea dominated stands. We used the chronosequence approach to test the influence of stand age and management on the SOC pool. Soil samples were systematically collected from 14 plots by means of a 70mm hand auger to a depth of max. 60cm and separated into five geometric horizons. Narrow O-layers and signs of active bioturbation on most sites suggest rapid carbon mineralisation. Carbon pools of the aboveground biomass, the O horizon as well as fine and coarse roots and decay were determined. Soils in our study are cambisols derived from fossil alluvial deposits and loess and calcic chernozems derived from loess. Total soil carbon was determined by means of dry combustion and subtraction of soil inorganic carbon (SIC, by means of the Scheibler-method) if present. Mean SOC contents ranged from 5.3 kg.m-2 to10.4 kg.m-2 in the entire study area. The highest contents were found in calcic chernozem sites (7.2-10.4 kg.m-2) followed by loamy cambisol (6.1-6.8 kg.m-2) and sandy cambisol sites (5.3-6.9 kg.m-2). Among three chronosequence sets, we found strong positive correlations with total nitrogen (Pearson correlation coefficients of +0.91 to +0.93, $p<0.01$) and medium strong positive correlations with fine root content (+0.27 to +0.42, $p<0.01$). In both cases, stronger correlations were observed at cambisol sites. Further medium correlations were found between SOC and decay (+0.23 to +0.42, $p<0.01$), but no influence of the soil type was observed. As expected, SOC contents decreased significantly with increasing soil depth. Tighter C/N ratios in deeper horizons suggest ongoing decomposition of soil organic matter (SOM). Total carbon pools analysis revealed a decline of the share of SOC on total carbon pool with increasing stand age and an increase in aboveground carbon in the vegetation ($r^2=0.88$). SOC accounted for 34-66 percent of the total carbon pool. In our study, the main determinants of SOC are soil type, soil depth and fine root content. Our results suggest that forest management (coppice with standards vs. high forest system) in deciduous forests in the northeastern lowlands of Austria has no decisive influence on soil carbon pools.

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Geophysical Research Abstracts
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EGU General Assembly 2011

Impact of forest stand management on temporal dynamics of soil carbon and nitrogen

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The quantity and quality of soil organic matter (SOM) strongly influence the biomass production capacity of forest ecosystems. At present, increased biomass harvesting for energetic utilisation is a hot topic. The extraction of logging residues, which are left on site in traditional forest management in Austria, and shortening of rotation periods will potentially alter carbon (C) and nitrogen (N) mineralization rates and turnover. This study focuses on i) assessing the influence of different forest management systems for deciduous species on soil C- and N stores and mineralization potential along a full rotation period and ii) testing whether silvicultural systems can be used to manage N retention and release. The chronosequence approach was used to study temporal dynamics of C and N on differently managed, *Quercus petraea* dominated forest sites (high forest on eutric cambisol, 11-91years as well as coppice with standards system on haplic chernozem, 1-50years). Above- and belowground biomass pools as well as belowground organic C- and total N pools (in five geometric horizons, up to 50cm depth) were estimated by means of systematic sampling of the soil and use of allometric functions for biomass pools. C was determined by dry combustion (soil organic carbon (SOC) and N by Kieldahl digestion (soil total N). SOC pools ranged from 5.3 to 6.9kg.m^{-2} on eutric cambisol, representing 43% of total site C stores and from 7.2 to 10.4kg.m^{-2} on haplic chernozem, representing 42% respectively. Total N stores in the mineral soil compartment ranged from 0.36 to 0.45kg.m^{-2} and from 0.65 to 0.94kg.m^{-2} for the two soil types. No significant correlation with stand age was observed for C and N pools in both study areas. However, C/N ratios as a measure for nitrogen availability show distinct temporal trends along the chronosequence in differently managed stands. The high forest system shows a gradual decrease of C/N ratio with increasing stand age in all horizons while the coppice with standards system shows a decrease until about half of the rotation period after which it increases again to the end of the rotation period. Wide C/N ratios at the beginning of rotation periods indicate rapid mineralization rates after harvesting. In the high forest on eutric cambisol sites, the C/N ratio is predominantly correlated with C (Pearson correlation coefficient of R=+0.70, $p<0.01$) in contrast to N (R=+0.17, $p<0.01$). Conversely, the C/N ratio in the coppice with standards on haplic chernozem is predominantly correlated with N (R=-0.33, $p<0.01$) in contrast to C (R=+0.20, $p<0.01$). A general trend of higher C/N ratios in the high forest indicates higher accumulation rates for C than for N. C/N ratios around 30-35 (<20 in mineral soil) indicate rapid litter decomposition under both silviculture regimes. The ratio between aboveground (living biomass, litter) and belowground carbon pools (SOC, roots, decay) generally increases with rising age and is always higher in coppice with standards system due to remaining standards after harvesting. This effect offsets nearly 10 years of stand development in the high forest system. We were able to identify clear patterns of C- and N dynamics resulting from different management regimes in different soil types on our study sites. The retention and release of nitrogen could be regulated by appropriate silvicultural systems, which should be considered when increased biomass extraction for energetic use becomes the management goal.

Keywords: SOC, C/N ratio, mineralization, forest management, *Quercus.*

Presented at the General Assembly of the European Geosciences Union, 03-08 April 2011, Vienna, Austria.

Geophysical Research Abstracts
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EGU General Assembly 2012

Carbon pools and temporal dynamics along a rotation period in sessile oak dominated high forest and coppice with standards stands

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Carbon pools in two *Quercus petraea* (sessile oak) dominated chronosequences under different forest management (high forest and coppice with standards) were investigated. The objective was to study temporal carbon dynamics, in particular carbon sequestration in the soil and woody biomass production, in common forest management systems in eastern Austria along with stand development. The chronosequence approach was used to substitute time-for-space to enable coverage of a full rotation period in each system. Carbon content was determined in the following compartments: aboveground biomass, litter, soil to a depth of 50 cm, living root biomass and decomposing residues in the mineral soil horizons. Biomass carbon pools, except fine roots and residues, were estimated using species-specific allometric functions. Total carbon pools were on average 143 Mg ha^{-1} in the high forest stand (HF) and 213 Mg ha^{-1} in the coppice with standards stand (CS). The mean share of the total organic carbon pool (TOC) which is soil organic carbon (SOC) differs only marginally between HF (43.4%) and CS (42.1%), indicating the dominance of site factors, particularly climate, in controlling this ratio. While there was no significant change in O-layer and SOC stores over stand development, we found clear relationships between living biomass (aboveground and belowground) pools and C:N ratio in topsoil horizons with stand age. SOC pools seem to be very stable and an impact of silvicultural interventions was not detected with the applied method. Rapid decomposition and mineralization of litter, indicated by low O-horizon pools with wide C:N ratios of residual woody debris at the end of the vegetation period, suggests high rates of turnover in this fraction. CS, in contrast to HF benefits from rapid resprouting after coppicing and hence seems less vulnerable to conditions of low rainfall and drying topsoil.

Keywords: carbon dynamics; soil carbon; chronosequence; *Quercus petraea*; coppice; high forest

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Lessons to be learned from the past: Forest biomass utilization and its belowground consequences

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Biomass was the major source of energy until the utilization of fossil energy. Its availability is strongly linked to the rise, prosperity and fall of former civilizations. Biomass from forests became scarce in many countries as the industry developed, leading to increasing transport distances from biomass sources and vast deforested patches of land along streams. There is good evidence from the past that unsustainable biomass extraction and consequent soil degradation had significant impact on soil properties in specific cases. In Central Europe, large quantities of forest biomass were not only used as timber, fuel and raw materials for trade but were also used in agriculture. Litter raking and pollarding were common practices until the mid of the last century. More plant nutrients were extracted from forest ecosystems to sustain the human population by setting up forest pastures and harvesting of edible parts of plants as fodder utilization. Starting from the Bronze Age, mining and proto-industrialization had a significant impact on forest ecosystems mainly because of the rising demand on fuelwood, charcoal and woodash. Such historical practices led to significant base-cation loss in many forest ecosystems and subsequently to soil acidification and reduced growth. Consequences of such practices should be kept in mind when evaluating the impact of harvesting residues management (utilization of slash) which is currently discussed as a measure to lessen dependency on fossil fuels and reduce greenhouse gas emissions.

Presented at the General Assembly of the European Geosciences Union, 22-27 April 2012, Vienna, Austria.

Nutritional status of *Quercus* dominated forest ecosystems for Biomass production

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Forest Biomass is seen as a key source for clean energy and as a raw material for industrial processes to combat climate change. Unlike fossil energy sources, Biomass has relatively low energy contents per volume unit, leading to increased demands near to potential customers. We studied nutrient pools in deciduous *Quercus* dominated forest ecosystems which are located near to the capital of Austria, Vienna. Recently, biomass potentials as well as consequences of biomass extraction gained increasing scientific attention at these forest sites. The studied forest ecosystems are embedded in an area intensively used for agriculture and relatively fertile soils (Haplic luvisols, chernozems) and receive considerable amounts of nitrogen through aerial deposition (7.6-9.4 kg ha a^{-1}). Our aim was to assess the current nutritional status of the forest in order to determine the effects of increased biomass extraction, specifically of nutrient-rich compartments such as foliage, thin branches and twigs and bark which are typically left on site under current forest management practices. Preliminary results show that there is a good logarithmic correlation between the wood diameter and the wood/bark mass ratio, typically ranging from around 1 at d=3mm for all species to 5 at d=10mm for *Quercus petraeae* and 5-6 at d~15mm for main understory species such as *Carpinus betulus* and *Corylus avellana*. In general, foliage had the highest contents of macronutrients N, P and K for all species followed by regenerative compartments, bark and wood. In general, *Q. petraeae* had the lowest macronutrient contents of P and K. In case of N, *C. avellana* has slightly lower contents as compared to the other species. Based on this results, and soil nutrient pools and deposition rates, we will evaluate the biomass production capacities and develop forest management guidelines aiming at sustainable biomass production.

W06.01-P -1

BIOMASS UTILIZATION AND ITS CONSEQUENCES ON SOILS – THE RETROSPECT VIEW

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Biomass was the major source of energy until the early utilization of fossil energy sources. Its availability is strongly linked to the development, prosperity and extinction of former civilizations. Biomass from forests became scarce as the industry developed, leading to increasing transport distances from biomass sources and vast deforested patches of land along streams. There is good evidence from the past that unsustainable biomass extraction and consequent soil degradation had significant impact on soil properties in specific cases. In central Europe, litter raking and pollarding were common practices until the mid of the last century. Nutrients were directly extracted from forest ecosystems to sustain the human population by setting up forest pastures and harvesting of edible parts of plants. Starting from the bronze age, mining and proto-industrialization had significant impacts on forests because of the rising demand on fuelwood, charcoal and even woodash. Such historical practices led to significant base cation loss in many forest ecosystems and consequently to soil acidification and reduced growth potential. Consequences of such practices should be kept in mind when evaluating the impact of harvesting residues management (utilization of slash) which is extensively discussed at the moment.

Presented at the 4th International Congress of the European Confederation of Soil Science Societies (ECSSS) 2-6 July 2012, Bari, Italy

S07.05-P -2

CARBON POOLS AND TEMPORAL DYNAMICS ALONG A ROTATION PERIOD IN QUERCUS DOMINATED HIGH FOREST AND COPPICE WITH STANDARDS STANDS

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Carbon pools in two Quercus petraea (sessile oak) dominated chronosequences under different forest management were investigated. The objective was to study temporal carbon dynamics in common forest management systems in eastern Austria along with stand development. The chronosequence approach was used to enable coverage of a full rotation period in each system. Carbon content was determined in the following compartments: aboveground biomass, litter, soil to a depth of 50 cm, living root biomass and decomposing residues in the mineral soil horizons. Total carbon pools were on average 143 Mg ha-1 in the high forest stand (HF) and 213 Mg ha-1 in the coppice with standards stand (CS). The mean share of the total organic carbon pool (TOC) which is soil organic carbon (SOC) differs only marginally between HF (43.4%) and CS (42.1%), indicating the dominance of site factors, particularly climate, in controlling this ratio. While there was no significant change in O-layer and SOC stores over stand development, we found clear relationships between living biomass pools and C:N ratio in topsoil horizons with stand age. SOC pools seem to be very stable and an impact of silvicultural interventions was not detected. Rapid decomposition and mineralization of litter, indicated by low O-horizon pools with wide C:N ratios of residual woody debris at the end of the vegetation period, suggests high rates of turnover in this fraction. CS, in contrast to HF benefits from rapid resprouting after coppicing and hence seems less vulnerable to conditions of low rainfall and drying topsoil.

Scientific CV

Curriculum Vitae

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Nationality:	Austrian
Marital status:	Married, 1 child

Tertiary Education

Since 2006: Ph.D. student in forest ecology (Project title: Carbon dynamics in coppice with reserves stands, coppice with standards stands and high forest managed for energetic biomass utilisation)

31.05.2006: Dipl.-Ing. degree (M.Sc. equivalent) in forest sciences at the University of Natural Resources and Life Sciences, Vienna. Title of diploma thesis: 'Rooting of three tree species and soil mineralogy at Pasoh Forest Reserve, Malaysia'.

04.10.2005: B.Sc. degree in forestry, University of Natural Resources and Life Sciences, Vienna

Languages

- German (native language)
- English (conference level)
- Mandarin & Chinese dialect of Hakka (basic level)

Current employment (full-time)

Since 10/2006: Commission for Interdisciplinary Ecological Studies (KIÖS), Austrian Academy of Sciences (ÖAW), Vienna, Austria

Function: Assistant to chairman, Research associate (Project administration, –acquisition and scientific assistance, scientific and administrative reporting, information management, public relations, conference and meeting organization)

Fields of major scientific interests and experience

Forest ecology, soil science, carbon management and turnover with focus on belowground processes, element cycles in forest ecosystems, biodiversity, biomass and bioenergy, biochar amendment.

Selected presentations, first author (P= Poster, L= Lecture)

Bruckman, Viktor J., and Yan, Shuai (21.05.2012) Nutritional status of *Quercus* dominated forest ecosystems for biomass production. Joint International Conference "Biological Reactions of Forests to Climate Change and Air Pollution", Kaunas, Lithuania. (L)

Bruckman, Viktor J., and Glatzel, Gerhard (23.04.2012) Lessons to be learned from the past: Forest biomass utilization and its belowground consequences. EGU General Assembly 2012, Vienna, Austria. (L+P)

Bruckman, Viktor J. et al. (23.04.2012) Carbon pools and temporal dynamics along a rotation period in sessile oak dominated high forest and coppice with standards stands. EGU General Assembly 2012, Vienna, Austria. (L+P)

Bruckman, Viktor J. (09.02.2012) Bioenergy from Forests: Carbon and nutrient dynamics in *Quercus* dominated coppice and high forests. Seminar for professors and students at the Tokyo University, Kashiwa Campus, Kashiwa, Japan. (L)

Bruckman, Viktor J. (06.02.2012) Nutritional status, carbon pools and temporal dynamics along a rotation period in differently managed *Quercus* forest ecosystems. KORANET Joint Call Partnering Event, Seoul, South Korea. (L)

Bruckman, Viktor J., and Yan, Shuai (06.04.2011) Impact of forest stand management on temporal dynamics of soil carbon and nitrogen. EGU General Assembly 2011 (European Geoscioences Union (EGU)), Vienna, Austria. (P)

Bruckman, Viktor J. et al. (27.01.2011) Kohlenstoffhaushalt in eichendominierten Mittelwaldbeständen und hochwaldartigen Beständen im Weinviertel. Mitteleuropäische Biomassekonferenz 2011 (Österreichischer Biomasseverband), Graz, Austria. (P)

Bruckman, Viktor J. (14.12.2010) Carbon dynamics in *Quercus* dominated coppice and high forests of Eastern Austria. PhD candidates seminar I. University of Life Sciences (BOKU), Vienna. (L)

Bruckman, Viktor J. (09.2010) Sustainable forest management in Austria: Challenges in the context of historic land use. 06.09.2010: Northwest Agriculture and Forestry University, Yangling, China. 16.09.2010: Northeast Forestry University, Harbin, China. 21.09.2010: Beijing Forestry University, Beijing, China. 21.09.2010: Chinese Academy of Forestry, Beijing, China. (all L)

Bruckman, Viktor J. et al. (24.08.2010) Rooting of selected tree species at Pasoh Forest Reserve, Malaysia. XXIII IUFRO World Congress — Forests for the Future — Sustaining Society and the Environment (IUFRO (International Union of Forest Research Organizations)), Seoul, South Korea. (P)

Bruckman, Viktor J. (24.08.2010) Soil mineralogy and its ecological consequences at Pasoh Forest Reserve, Malaysia. XXIII IUFRO World Congress — Forests for the Future — Sustaining Society and the Environment (IUFRO (International Union of Forest Research Organizations)), Seoul, South Korea. (P)

Bruckman, Viktor J. (07.07.2009) Agrofuels between Sustainability and Development — Interdisciplinary Analysis — Holistic Approach. International Symposium on Nutrient Management and Nutrient Demand of Energy Plants (Corvinus University Budapest/ International Potash Institute (IPI)), Budapest, Hungary. (L)

Bruckman, Viktor, J. (09.10.2008) Agrofuels — at the area of tension between sustainability and development policy. Biofuels Production: ecological, economic and technical aspects. Moscow, Russian Federation. (L)

Bruckman, Viktor J. (25.05.2006) Rooting of three tree species and soil mineralogy at Pasoh Forest Reserve, Malaysia. Diploma seminar at University of Natural Resources and Life Sciences, Vienna. (L)

Bruckman, Viktor J. (06.02.2006) Density and distribution of fine and medium roots in selected key tree species at Pasoh Forest Reserve. Pasoh activities meeting, FRIM (Forest Research Institute of Malaysia), Kepong, Kuala Lumpur, Malaysia. (L)

Teaching experience

- [2010] Carbon in forest ecosystems: Pools – assessment approaches – analytical methods – interpretation. Lecture: Ecology of Mountain Forests I: Mountain forest soils and forest nutrition. University of Life Sciences (BOKU), Vienna.
- [2010] Introduction to an automated reference management and citing system: EndNote X4. Beijing Forestry University, Beijing,China.
- [2009] Agrofuels – Potential to contribute to a fair and sustainable future? Lecture: Alternative Technologies & Renewable Resources for a sustainable Development, Leibnitz, Austria.
- [2008] Tropische Regenwälder – Brennpunkte der Diversität [Tropical rain forests – hotspots of diversity]. Lecture: Volkshochschule Wien [College of further education Vienna], Organized in the framework of the University meets public (UPM) programme, Vienna, Austria.
- [2004-2005] Tutor at the Institute of Silviculture, University of Life Sciences (BOKU), Vienna. Lecture and fieldwork: Waldbau [Silviculture].

Project experience

2012-now: Potentials for realizing negative carbon emissions using forest biomass for energy and subsequent biochar recycling (funded by EU FP7 under the KORANET initiative) [Project initiation and coordination of consortium consisting of partners from Austria, South Korea and Turkey] [project status: grant received 07/2012]

2009-now: Carbon turnover in *Quercus* ecosystems in view of biomass production for energetic utilization (funded by Federal Ministry of Agriculture, Forestry, Environment and Water Management, Austria and Austrian Academy of Sciences, ÖAW) [Project leader]

2007-2009: Investigations on the dynamics of biomass and carbon pools in coppice with reserves stands, coppice with standards stands and high forest (funded by Federal Ministry of Agriculture, Forestry, Environment and Water Management, Austria) [Workgroup coordinator]

2008-2009: Biofuels – at the area of tension between sustainability and development policy (funded by Austrian Academy of Sciences, ÖAW) [Project leader]

Functions in scientific journals/societies

- Interdisciplinary Perspectives (launched in 2011 at ÖAW) [Series editor, since 2011]
- International Research Journal of Agricultural Science (IRJAS) [Reviewer, since 2011]
- Polish Journal of Environmental Studies (PJOES) [Reviewer, since 2009]

- European Geoscience Union [EGU], Division on Energy, Resources and the Environment (ERE) [Board member and scientific officer for surface processes, since 2011]
- International Union of Forest Research Organizations (IUFRO), Taskforce Forest Bioenergy [Member – Division 7 (Forest Health) representative, since 2010]

- International Union of Forest Research Organizations (IUFRO) [Deputy Coordinator: WG 7.01.03 – Impacts of air pollution and climate change on forest ecosystems – Atmospheric deposition, soils and nutrient cycles, since 2010]

Membership in scientific and professional societies

- Global Soil Biodiversity Initiative (GSBI) [since 2012]
- Österreichische Bodenkundliche Gesellschaft (ÖBG) [since 2011]
- International Union of Forest Research Organizations (IUFRO) [Officeholder, since 2010]
- European Geosciences Union (EGU) [Officeholder, since 2010]
- Platform Biodiversity Research Austria (BDFA) [since 2008]

Conference/Event organization (selection)

- Aspects of Biomass utilization from Forests and other Resources. Session ERE 1.8 of the European Geosciences Union (EGU) General Assembly 2012, including a poster and a poster discussion session, 23.04.2012, Vienna, Austria (Convener) [scientific event]
- Heiliges Wasser – Hochwasser – Niedrigwasser – Giftwasser: Ein Nachmittag zum Thema Wasser in einer sich ändernden Welt [Holy water – High water – Low water – Bad water: Water in a changing world], 21.01.2011, Vienna, Austria (Scientific committee; chairman organizing committee) [public event]
- Lange Nacht der Forschung – Beitrag der KIÖS [Long night of science – contribution of KIÖS], 07.11.2009-08.11.2009, Vienna, Austria (Chairman scientific and organizing committee) [public event]
- Kerner von Marilaun Workshop 2009: Landscape-Based Cultural Ecosystem Services, 02.11.2009-06.11.2009, Lunz am See, Austria (organizing committee) [scientific event]
- Vom Umgang mit den Ressourcen [Management of natural resources], 09.12.2008, Vienna, Austria (chairman organizing committee) [public event]
- Kerner von Marilaun Workshop 2007: The challenge of sustaining soils: lessons from historical experience for a sustainable future, 08.11.2007-09.11.2007, Vienna, Austria (organizing committee) [scientific event]
- Vom Waldessen und Waldbrennen [The utilization of forest resources], 24.10.2007, Vienna, Austria (organizing committee) [public event]

Selected publications (P= papers, C= book chapters, R= reports and A= abstracts)

Bruckman, Viktor J., and Wriessnig, Karin (2012) Improved soil carbonate determination by FT-IR and X-ray analysis. Environmental Chemistry Letters. [online first, DOI: 10.1007/s10311-012-0380-4] (P)

Bruckman, Viktor J., Yan, Shuai, Hochbichler, Eduard, and Glatzel, Gerhard (2012) Considerations for Sustainable Biomass Production in *Quercus*-dominated Forest Ecosystems. In: Matovic M.D. (Ed.) Biomass. [submitted] (C)

Ramirez, Kelly S., Bardgett, Richard D., Fricks, Barbara, Montanerella, Luca, Six, Johan, van der Putten, Wim H., Wall, Diana H., Ameloot, Nele, Ayuke, Fredrick, Banwart, Steven A., Bignell, David E., Black, Helaina, Bossio, Deborah, **Bruckman, Viktor J.** et al. (2012) White Paper on the First Open

Meeting of the Global Soil Biodiversity Initiative (GSBI) held in London, England, 30 March 2012, GSBI. (P)

Bruckman, Viktor J., and Yan, Shuai (2012) Nutritional status of *Quercus* dominated forest ecosystems for Biomass production. Biological Reactions of Forests to Climate Change and Air Pollution, p 55. (A)

Bruckman, Viktor J., and Glatzel, Gerhard (2012) Lessons to be learned from the past: Forest biomass utilization and its belowground consequences. Geophysical Research Abstracts Vol. 14; EGU2012-12535; Copernicus Publications, Göttingen, Germany. (A)

Bruckman, Viktor J., Yan, Shuai, Hochbichler, Eduard, Glatzel, Gerhard (2012) Carbon pools and temporal dynamics along a rotation period in sessile oak dominated high forest and coppice with standards stands. Geophysical Research Abstracts Vol. 14; EGU2012-5437; Copernicus Publications, Göttingen, Germany. (A)

Yan, Shuai, **Bruckman, Viktor J.**, Glatzel, Gerhard, Hochbichler, Eduard (2012) Assessment of forest nutrient pools in view of biomass potentials – a case study from Austrian oak stands. Geophysical Research Abstracts Vol. 14; EGU2012-5205; Copernicus Publications, Göttingen, Germany. (A)

Bruckman, Viktor J., Yan, Shuai, Hochbichler, Eduard, and Glatzel, Gerhard (2011) Carbon pools and temporal dynamics along a rotation period in *Quercus* dominated high forest and coppice with standards stands. Forest Ecology and Management, 262, p. 1853-1862. (P)

Bruckman, Viktor J., Yan, Shuai, Hochbichler, Eduard, and Glatzel, Gerhard (2011) Impact of forest stand management on temporal dynamics of soil carbon and nitrogen. European Geosciences Union (EGU) General Assembly 2011). Geophysical Research Abstracts Vol. 13; Copernicus Publications, Göttingen, Germany. (A)

Yan, Shuai, **Bruckman, Viktor J.**, and Glatzel, Gerhard, Hochbichler, Eduard (2011) A chronosequence approach to study stand age effects on total nitrogen as well as exchangeable K, Ca and Mg in the soils in view of increased energetic utilization of *Quercus* dominated forests in northeastern Austria. European Geosciences Union (EGU) General Assembly 2011). Geophysical Research Abstracts Vol. 13; Copernicus Publications, Göttingen, Germany. (A)

Bruckman, Viktor J., Hochbichler, Eduard, and Glatzel, Gerhard (2011) Kohlenstoffhaushalte in eichendominierten Mittelwaldbeständen und hochwaldartigen Beständen im Weinviertel. [Carbon budgets in oak-dominated coppice and pseudo-high forests in the Austrian Weinviertel area]. Proceedings – Central European Biomass Conference 2011, 26th–29th January, Graz, Austria, p. 139. (A)

Yan, Shuai, **Bruckman, Viktor J.**, Glatzel, Gerhard, and Hochbichler, Eduard (2011) Nutrient Pools in Oak Forests as a decision support for harvesting intensities (Biomass potential). Abstract, Proceedings – Central European Biomass Conference 2011, 26th–29th January, Graz, Austria, p. 182. (A)

Bruckman, Viktor J., Hochbichler, Eduard, Yan, Shuai, and Glatzel, Gerhard (2010) Determinants of soil organic carbon pools in oak stands in Northeastern Austria. Geophysical Research Abstracts 12, EGU2010-11388-3, EGU General Assembly 2010. (A)

Yan, Shuai, **Bruckman, Viktor J.**, and Glatzel, Gerhard (2010) Exchangeable Cations in the Soils of *Quercus* Dominated Forests in Northeastern Austria. Geophysical Research Abstracts 12, EGU2010-13772-3, EGU General Assembly 2010. (A)

Yan, Shuai, Glatzel, Gerhard, and **Bruckman, Viktor J.** (2010) A comparison of selected soil properties under high and coppice forest in the Vienna Woods. Abstract, The International Forestry Review 12 (5), p. 89. (A)

Bruckman, Viktor J., Ottner, Franz, and Wriessnig, Karin (2010) Soil mineralogy and its ecological consequences at Pasoh Forest Reserve, Malaysia. Abstract, The International Forestry Review 12 (5), p. 247. (A)

Bruckman, Viktor J., and Glatzel, Gerhard (2010) Rooting of selected tree species at Pasoh Forest Reserve, Malaysia. Abstract, The International Forestry Review 12 (5), p. 247. (A)

Bruckman, Viktor J. (2010) Auswirkungen der Biokraftstoffproduktion in Entwicklungsländern [Effects of biofuel production in developing countries]. Paradigmata – Zeitschrift für Menschen und Diskurse 2 , pp. 44-48 (P)

Hochbichler, Eduard, **Bruckman, Viktor J.,** Glatzel, Gerhard, and Spinka, Stefan (2009) Untersuchungen zur Dynamik der Biomassen- und Kohlenstoffvorräte in Niederwäldern mit Überhältern, Mittel- und Hochwäldern [Investigations to the dynamics of the biomass and carbon pools in coppice with reserves stands, coppice with standards stands and high forest]. Report no. 100185; University of Natural Resources and Applied Life Sciences, Department for forest and soil sciences: Vienna; commissioned by: Federal Ministry of Agriculture, Forestry, Environment and Water Management. 154 pages. (R)

Bruckman, Viktor J., and Habermann, Birgit (2009) Agrofuels between Sustainability and Development. Proceedings, International Symposium on Nutrient Management and Nutrient Demand of Energy Plants; Budapest, pp 14. (A)

Bruckman, Viktor J., and Habermann, B. (2008) Agrofuels- Between Sustainability and Development. Definitions, Analysis and Protagonists from the Point of View of Science and Research. KEF Fact Sheet 1/08, Austrian Academy of Sciences, Vienna. 15 pages. (P)

Bruckman, Viktor J. (2006) Rooting of three tree species and soil mineralogy at Pasoh Forest Reserve, Malaysia. Institute for Forest Ecology. BOKU, Vienna. 131 pages. [diploma thesis] (R)

Abstract

Carbon (C) is an essential element for all forms of life we know and its reduced or not fully oxidized forms are the major source of energy used by humans. At the same time it is at centre stage in context of climate change and subsequent negative consequences for humanity. Forests represent the largest pool of terrestrial C, directly situated at the reactive soil-atmosphere interface and their management has the potential to significantly influence atmospheric C concentrations. The aim was to highlight the importance of forests in the global C cycle and to study C pool dynamics along a stand development in view of C management. The present work consists of three parts:

Part 1 presents a holistic overview on current knowledge of anthropogenic C metabolism and the resulting climate change. The role of forests in sequestering C is emphasised in context of forest management and biomass production for energetic utilization. Promising examples of different strategies to maximize C sequestration are presented and discussed.

Part 2 comprises a paper on dynamics of organic C pools along a rotation period in two *Quercus*-dominated chronosequences in a high forest and coppice management system. The results suggest that soil organic carbon (SOC) pools are relatively low in both systems and the impact of logging on SOC is low. Fine root dynamics differ remarkably between the two silvicultural management systems. The chronosequence approach was suitable to describe aboveground biomass C pools but it turned out that it is an inappropriate method to study SOC dynamics in the proposed study setup.

Part 3 proposes an improved method to assess soil inorganic carbon (SIC) on the same plots. The current, gas-volumetric Scheibler method has a number of disadvantages. Hence a new approach of combining Fourier Transform Mid-Infrared Spectroscopy (FT-MIR) and X-ray diffraction (XRD) and subsequent partial least squares regression (PLSR) modelling is presented. The model shows a good performance in predicting carbonate contents across the study region. A combination of the two methods FT-MIR and XRD has the potential to improve accuracy of SIC determination.

Keywords: Climate change, Biomass, Carbon, *Quercus petraea*, Chronosequence, Carbonate