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Auswirkung der Rückführung von Kurzumtriebsplantagen in Acker- und Grünlandnutzung auf Boden C-Fraktionen

Dissertation

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Charlotte Tönshoff

Vorwort

Die vorliegende Dissertation wurde im Rahmen des Projektes „KURZUM - Dynamik von Boden C- und N-Fraktionen und pflanzlicher Produktivität während der Überführung von Kurzumtriebsplantagen (KUP) in Acker- oder Grünlandnutzung“, gefördert vom Hessischen Ministerium für Umwelt, Energie, Landwirtschaft und Verbraucherschutz sowie der Volkswagen AG, an der Universität Kassel im Fachbereich Ökologische Agrarwissenschaften im Fachgebiet Bodenbiologie und Pflanzenernährung angefertigt. Die Arbeit besteht aus 3 Papern, von denen eins bereits bei einer internationalen, begutachteten Fachzeitschrift zur Veröffentlichung angenommen wurde und zwei weiteren, die zur Veröffentlichung eingereicht sind. Die Paper sind in Kapitel 4, 5 und 6 eingearbeitet. Kapitel 1 gibt eine generelle Einleitung zum Thema, während im Kapitel 2 der angelegte Feldversuch vorgestellt wird. Das Kapitel 3 stellt die Ziele dieser Arbeit heraus. In Kapitel 7 und 8 werden die wichtigsten Ergebnisse aus Kapitel 4, 5 und 6 auf Deutsch sowie auf Englisch zusammenfassend dargestellt. Kapitel 9 beinhaltet die Schlussfolgerungen, die sich aus den Untersuchungen dieser Arbeit ergaben und gibt einen Ausblick für weitere Untersuchungen.

Die folgenden Artikel sind Bestandteil der vorliegenden Arbeit:

Kapitel 4

Toenshoff, C., Joergensen, R.G., Stuelpnagel, R., Wachendorf, C. (2012) Carbon in plant biomass and soils of poplar and willow plantations - implications for SOC distribution in different soil fractions after re-conversion to arable land. Plant and Soil DOI: 10.1007/s11104-012-1481-3

Kapitel 5

Toenshoff, C., Joergensen, R.G., Stuelpnagel, R., Wachendorf, C. (2012) Dynamics of soil organic carbon fractions one year after the re-conversion of poplar and willow plantations to arable use and grassland. Agriculture, Ecosystems and Environment (submitted)

Kapitel 6

Toenshoff, C., Joergensen, R.G., Stuelpnagel, R., Wachendorf, C. (2012) Initial decomposition of post-harvest residues of poplars as affected by N availability and particle size. Biology and Fertility of Soils (submitted)

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Abkürzungsverzeichnis

$AlCl_3$	Aluminiumchlorid
ANOVA	Varianzanalyse
ASL	Über dem Meeresspiegel
$BaCl_2$	Bariumchlorid
C	Kohlenstoff
$CaCl_2$	Calciumchlorid
$CHCl_3$	Chloroform
CO_2	Kohlendioxid
C_{org}	Organischer Kohlenstoff
C_{mik} (C_{mic})	Mikrobieller Biomasse Kohlenstoff
CV	Variationskoeffizient
DM	Trockenmasse
DW	Trockengewicht
fLF	Freie leichte organische Fraktion
HCL	Salzsäure
K_2SO_4	Kaliumsulfat
k_{EC},k_{EN}	Extrahierbarer Teil des Gesamtkohlenstoffs und -stickstoffs gebunden in der mikrobiellen Biomasse
KUP	Kurzumtriebsplantage
M	mol/L
LF	Leichte organische Fraktion
N (N_t)	Stickstoff (Stickstoff-Gesamtgehalt)
NN	Normal-Null
NaCl	Natriumchlorid
Na_2CO_3	Natriumcarbonat

NaOH	Natronlauge
NH_4^+	Ammonium
NH_4NO_3	Ammoniumnitrat
N_{mik} (N_{mic})	Mikrobieller Biomasse Stickstoff
NO_3^-	Nitrat
oLF	Okkludierte leichte organische Fraktion
POM	Partikuläres organisches Material
SOC	Organischer Bodenkohlenstoff
SPT	Sodiumpolytungstate
WHK (WHC)	Wasserhaltekapazität

1. Einleitung

Die steigenden Preise für fossile Energieträger und die Verwendung erneuerbarer Energiequellen als ein wichtiger Bestandteil der Klimaschutzstrategien führten in jüngster Zeit zu einem gesteigerten Interesse an der Produktion holziger Biomasse aus Kurzumtriebsplantagen (KUP) (Bemmann et al. 2007; BMELV 2008).

KUPs sind dichte, reihenartige Anpflanzungen schnellwachsender Baumarten wie Pappeln oder Weiden auf zumeist ehemals landwirtschaftlichen Flächen zur Produktion holziger Biomasse. Nach einmal erfolgter Kulturbegründung wird in regelmäßigen Umtriebszeiten von 2 bis zu 20 Jahren die oberirdische Sprossmasse geerntet und die Bäume treiben aus dem im Boden verbleibenden Wurzelstock wieder aus, ohne dass sie neu angepflanzt werden müssen (Kauter et al. 2003; Knust 2009; Dimitriou et al. 2009). Die Biomasse der Pappeln und Weiden kann als Energieholzhackschnitzel, Pellets oder Papierholz verwertet werden. Bei einer energetischen Verwendung des Holzes wird die Sprossmasse in Intervallen zwischen 2 und 6 Jahren geerntet, wohingegen bei einer stofflichen Verwertung des Holzes die Bewirtschaftung mit längeren Umtriebszeiten erfolgt (Kauter et al. 2003). Durch das Ausbleiben einer regelmäßigen Bodenbearbeitung und den erhöhten Eintrag von Laub- und Wurzelstreu können langjährig bewirtschaftete KUPs zu einer Akkumulation von organischen Kohlenstoff im Boden führen und eine temporäre Kohlenstoffsenke darstellen (Grogan und Matthews 2002; Lamersdorf et al. 2010; Garten 2011).

Soll die KUP Bewirtschaftung beendet und die Fläche wieder in konventionelle landwirtschaftliche Nutzung rückgeführt werden, erfolgt nach der letzten Holzernte eine intensive Bodenbearbeitung, um Wurzelstöcke, Grobwurzeln und Erntereste zu zerkleinern und in den Boden einzuarbeiten. Dadurch ist zum einem von einer gesteigerten Mineralisierung der unter KUP akkumulierten organischen Bodensubstanz auszugehen, andererseits werden hohe Mengen an grob zerkleinerten Ernteresten in den Boden eingearbeitet. Da bislang kaum Untersuchungen zur Auswirkungen der Rückführung von KUPs auf die Kohlenstoffdynamik im Boden vorliegen, ist nicht bekannt wie viel Kohlenstoff im Zuge der Rückführung freigesetzt und wie viel in welchen Bodenfraktionen über welchen Zeitraum gespeichert bleibt. Die vorliegende Arbeit soll einen ersten Beitrag dazu leisten diese bestehende Wissenslücke zu schließen, um praxistaugliche Bewirtschaftungspfade entwickeln zu können, die die Mineralisierung des unter KUPs akkumulierten organischen Kohlenstoffs durch die nachgelagerte Bodenbearbeitung vermindern.

1.1 C-Speicherung unter Kurzumtriebsplantagen

KUPs haben durch die ausbleibende Bodenbearbeitung, dem Wachstum der Wurzelstöcke sowie dem erhöhten Eintrag von Laub- und Wurzelstreu, das Potential organischen Kohlenstoff im Boden anzureichern (Grogan und Matthews 2002; Laganière et al. 2010; Lamersdorf et al. 2010). Kahle et al. (2007) ermittelten nach 12-jähriger KUP Bewirtschaftung auf einer ehemaligen Ackerfläche eine C-Anreicherung im Oberboden von 6 t C ha^{-1} und auch Roedl (2010) berechnete mit 19 t C ha^{-1} einen Anstieg der Menge des Bodenkohlenstoffs in ähnlicher Größenordnung während einer 20-jährigen KUP Nutzung. Allerdings ist es nicht möglich eine allgemein gültige Aussage über die Höhe des C-Speicherungspotential von KUPs zu treffen, da der Einfluss auf den C-Gehalt des Bodens von vielfältigen Faktoren, wie der Ausgangslage des Bodens, den Standortbedingungen und den Bearbeitungsmaßnahmen während der Bewirtschaftung beeinflusst wird (Coleman et al. 2004; Laganière et al. 2010). Darüber hinaus wird die Quantifizierung der C-Akkumulation während der KUP Bewirtschaftung gegenüber landwirtschaftlichen Flächen dadurch erschwert, dass zumeist vor Anlage der KUP der C-Gehalt des Bodens nicht erfasst wurde und oftmals keine geeigneten Referenzflächen vorhanden sind (Rödl und Schweinle 2010).

Des Weiteren beziehen sich vorliegende Untersuchungen lediglich auf den gesamten organischen Bodenkohlenstoff. Weitergehende Untersuchungen über die Verteilung der Kohlenstoffbindung in einzelnen Fraktionen des Bodens unter KUP liegen kaum vor. Ein erhöhter Eintrag von Laub- und Wurzelstreu führt in der Regel zu einem hohen Anteil an leichten, partikulären organischen Material an der organischen Bodensubstanz (Tan et al. 2007; Mao und Zeng 2010). Diese leichte organische Fraktion (LF) besteht aus jungen, noch relativ wenig zersetzten Pflanzenresten und repräsentiert einen sehr labilen C-Pool des Bodens der schnelle Umsatzzeiten aufweist (Haynes 2005). Die ausbleibende Bodenbearbeitung und der erhöhte Streueintrag unter KUP fördern darüber hinaus die biologische Aktivität (Schmitt et al. 2010; Pellegrino et al. 2011), wodurch von einer gesteigerten Bildung von Aggregaten im Boden zu rechnen ist (Six et al. 2000a; Devine et al. 2004). Gemäß der Theorie der Aggregathierarchie nach Tisdall und Oades (1982) werden Tonpartikel und organo-mineralische Komplexe durch von Pflanzenwurzeln und Mikroorganismen ausgeschiedenen Polysacchariden zu stabilen Mikroaggregaten (53-250 µm) verbunden. Größere Makroaggregate (> 250 µm) setzen sich wiederum aus frisch zugeführten Pflanzenresten und Mikroaggregaten zusammen die durch Pilzhyphen, Feinwurzeln und Ausscheidungsprodukte der Mikroorganismen verkittet werden.

Makroaggregate weisen daher einen hohen Anteil an partikulärer, leichter organischer Substanz auf, die innerhalb der Aggregate als okkludierte, leichte Fraktion (oLF) physikalisch gegenüber mikrobiellen Abbau stabilisiert wird (Six et al. 2000b).

Neben einer Akkumulation von C im Mineralboden führt das Wachstum der Wurzelstöcke der Bäume zu einer C-Festlegung in der Wurzelbiomasse. Angaben in der Literatur zur Menge der Wurzelbiomasse unter KUP variieren aufgrund der Vielzahl an Einflussfaktoren auf die Biomasseproduktion über einen weiten Bereich (Laganière et al. 2010; Garten 2011) und beruhen mit wenigen Ausnahmen, u.a. bei Fang et al. (2007) und Petzold et al. (2010), meist auf Modellierungen.

1.2 Rückführung von Kurzumtriebsplantagen

Werden KUPs mit einer maximalen Nutzungsdauer von 30 Jahren angebaut, gelten diese weiterhin als landwirtschaftliche Nutzfläche und werden nicht zu Wald. Danach können die Flächen in landwirtschaftliche Nutzung rückgewandelt werden oder nach einer Bestandsauflösung erneut als KUP etabliert werden (Knust 2009). Besteht die Aussicht profitablere Betriebsgewinne mit einer anderweitigen Nutzung der Fläche zu erzielen oder nach einem Zusammenbruch des Bestandes durch pilzliche Schaderreger oder Insekten (Kröber et al. 2010) ist jedoch auch mit einer Rückführung vor Erreichen der maximalen Nutzungsdauer zu rechnen (Grogan und Matthews 2002; Devine et al. 2006).

Bei der Rückwandlung von KUPs werden nach der letzten Ernte überstehende Wurzelstöcke und auf der Fläche verbliebene Holzreste mit einem Forstmulcher bodengleich gemulcht. Der Boden wird anschließend mit einer Rodungsfräse üblicherweise 30 cm tief gefräst, wobei die im Boden verbleibenden Wurzelstöcke zerkleinert und zusammen mit dem gemulchten Holz in den Boden eingearbeitet werden. Aufgrund dieser intensiven Bodenbearbeitung ist mit einer gesteigerten Mineralisierung der unter KUP akkumulierten organischen Bodensubstanz nach dem Umbruch zu rechnen, wie es nach einem Landnutzungswechsel von Wäldern oder Grünland in Ackerland oder nach dem Umbruch langjährig nicht bearbeiteter landwirtschaftlicher Böden in einer Vielzahl an Studien, u.a. bei Stockfisch et al. (1999) und Guo und Gifford (2002), berichtet wurde. Hohe C-Verluste wurden insbesondere aus den labilen C-Pools des Bodens, wie der leichten, frei im Boden vorliegenden partikulären organischen Fraktion (Okore et al. 2007; Yang et al. 2009) und der mikrobiellen Biomasse (Motavalli et al. 2000) beobachtet. Intensive Bodenbearbeitung führt außerdem zur Zerstörung von Makroaggregaten, so dass in den Makroaggregaten stabilisiertes

organisches Material freigesetzt und für den mikrobiellen Abbau verfügbar wird (Six et al. 1999). Gängige Methoden um den Abbau organischer Bodensubstanz in der Landwirtschaft zu mindern, sind daher die Reduzierung der Bodenbearbeitungstiefe (Kushwaha et al. 2001) oder die Nutzung als Grünland (Guo und Gifford 2002; Grandy und Robertson 2007).

Andererseits werden während der Rückwandlung von KUPs hohe Mengen an grob zerkleinerten Wurzeln und oberirdischen Holzresten in den Boden eingearbeitet (Scholz 2009). Es liegen allerdings keine Erfahrungswerte zu den Holzmengen vor, die dem Boden zusätzlich mit den oberirdischen Ernterückständen zugeführt werden. Aufgrund hoher Lignin und geringer N-Gehalte der holzigen Erntereste (Camire et al. 1991; Devine et al. 2006) ist von einem langsamen Abbau der Erntereste und somit von einer langen Verweilzeit im Boden auszugehen. Möglicherweise tragen die während des Abbaus freigesetzten Abbauprodukte der Erntereste längerfristig zum Aufbau von organischer Bodensubstanz bei (Kirschbaum et al. 2008) und mindern die zu erwartenden C-Verluste infolge des Umbruchs (Sanchez et al. 2007). Bislang liegen nur vereinzelt Studien über die zeitliche Abbaudynamik von verholzten, grob zerkleinerten Ernteresten (Wal et al. 2007; Müller-Using und Bartsch 2009) sowie der Stabilisierung des aus Ernteresten freigesetzten C in verschiedenen Bodenfraktionen (Sanaullah et al. 2011) vor. Zudem ist durch die Einarbeitung hoher Mengen an Ernteresten mit weiten C/N Verhältnissen eine mikrobielle N-Immobilisierung im Boden, was die pflanzenverfügbare N-Menge für die Nachfolgekulturen negativ beeinflussen kann, nicht auszuschließen (Devine et al. 2006; Kirschbaum et al. 2008).

2. Versuchsdurchführung

Um zu ermitteln, in welchen Bodenfraktionen der organische Kohlenstoff langjährig bewirtschafteter KUPs gespeichert ist und die Auswirkungen des Umbruchs und der Rückführung von KUPs in landwirtschaftliche Nutzung auf die Kohlenstoffdynamik im Boden zu untersuchen, wurde an zwei Standorten ein Feldversuch angelegt. Nachfolgend werden die Standorte sowie die Anlage und Durchführung des Feldversuches dargestellt. Eine detaillierte Beschreibung der angewandten Methoden befindet sich in den Kapiteln 4-6.

2.1 Standorte

Die Untersuchungen erfolgen am Standort Georgenhof bei Diemelstadt (51°27'N, 9°0'O, 320 m ü. N.N.) auf einer mit Pappeln und einer mit Weiden bestandenen KUP. Die Böden beider Untersuchungsflächen sind verbraunte Haftpseudogleye aus einer Lössfließerde über triassischen Buntsandstein, die auf der Weidenfläche in den ersten 30 cm durch 28% Sand, 61% Schluff und 11% Ton, gekennzeichnet ist, während sich die Textur auf der Pappelfläche aus 19% Sand, 64% Schluff und 17% Ton zusammensetzt. Die mittlere Jahrestemperatur beträgt 7,9°C bei mittleren Jahresniederschlagssummen von 740 mm. Die zweite Untersuchungsfläche in Wachtum liegt südwestlich von Cloppenburg (52°47'N, 7°44'O, 22 m ü. N.N.), die Jahresmitteltemperatur beträgt 9,0°C, der durchschnittliche jährliche Niederschlag 815 mm. Als Bodentyp liegt ein tiefumgepflügter Gley-Podsol aus holozänen Flugsanden, als Bodenart ein schwach schluffiger Sand mit 76% Sand, 20% Schluff und 4% Ton vor. Lange vor Etablierung der KUP wurden an diesem Standort Niedermoorreste tief in den Boden eingepflügt.

Die Plantagen wurden 1987 (Georgenhof) bzw. 1989 (Wachtum) auf ehemaligen Ackerflächen als Versuchsflächen vom Institut für schnellwachsende Baumarten angelegt, um verschiedene Weiden- (*Salix spp.*) und Pappelklone (*Populus spp.*) zu testen und bis 1998 in 3 bis 4-jährigen Rotationsperioden bewirtschaftet. Danach wurden die Flächen von einem Papierhersteller gepachtet und weiter bewirtschaftet. Eine Ernte erfolgte seit Übernahme der Flächen nicht mehr, da das Holz einer stofflichen Verwertung für die Schleifholzgewinnung zugeführt werden sollte, was höhere Stammdurchmesser erfordert.

Abb. 1 Kurzumtriebsplantagen der Standorte Georgenhof Weide, Georgenhof Pappel und Wachtum Pappel vor der letztmaligen Beerntung (von links)

Die ursprüngliche Pflanzdichte betrug auf der Weidenfläche am Georgenhof 15.385 Bäume ha^{-1} (1.3 x 0.5 m), auf der Pappelfläche 10.000 Bäume ha^{-1} (1 x 1 m). Auf der Pappelfläche in Wachtum wurden die Klone in Pflanzverbänden mit Abständen von 2.2 x 1.2 (3788 Bäume ha^{-1}) und 3.0 x 1.2 m (2777 Bäume ha^{-1}) gepflanzt. Aufgrund der Ausdünnung der Bestände nach der Jugendphase und zu den bisherigen Ernten sowie einer hohen Sterberate, betrug die Pflanzdichte vor der letzten Ernte 1296 Bäume ha^{-1} auf der Weidenfläche am Georgenhof, 1905 Bäume ha^{-1} auf der Pappelfläche am Georgenhof und 1942 Bäume ha^{-1} auf der Pappelfläche in Wachtum.

2.2 Versuchsanlage

Vor der letztmaligen Beerntung der KUPs wurden im Winter 2009/2010 die oberirdischen Pflanzenerträge erhoben sowie die Wurzelmengen ermittelt, um die in der gesamten Biomasse der Bäume gespeicherten C-Mengen zu bestimmen. Die Ertragserhebung der oberirdischen Biomasse erfolgte auf der Weidenfläche nach der Stockerntemethode durch Rodung dreier Weidenstöcke. Auf den beiden Pappelflächen wurden die oberirdischen Erträge (getrennt nach Stamm und Krone) nach der Regressionsmethode durch Rodung von jeweils fünf Probebäumen je Standort ermittelt. Die Bestimmung der Wurzelmengen erfolgte durch Rodung und Ausgrabung des gesamten Wurzeltellers der einzelnen Probebäume auf 1,4 x 1,4 m in einer Tiefe von 0,3 m und Trennung in einzelne Wurzelfraktionen

(Wurzelstock, Grobwurzeln > 5 mm und Feinwurzeln < 5 mm). Die letztmalige Beerntung der Weiden wurde im Mai 2010 motormanuell mit einer Motorsäge durchgeführt, die Ernte der beiden Pappelflächen erfolgte im Winter 2010 mittels Harvester. Zur Rückführung der Flächen in konventionelle landwirtschaftliche Nutzung wurden nach der Ernte in einem ersten Arbeitsgang überstehende Wurzelstöcke und auf der Fläche verbliebenes Stamm– und Kronenholz mit einem Forstmulcher zerkleinert (Abb. 2 links). Infolge der langen letzten Umtriebszeit von 12 Jahren fiel bei den Pappeln eine größere Mengen an oberirdischen Ernteresten in Form von höher geschnittenen Wurzelstöcken und abgebrochenen Ästen und bei den Weiden mehr Totholz an, als bei einer KUP Bewirtschaftung zur energetischen Verwendung des Holzes mit kürzeren Umtriebszeiten zu erwarten ist.

Abb. 2 Mulchen der oberirdischen Holzreste nach der letzten Ernte (links) und gemulchte Ernterückstände vor der Einarbeitung in den Boden im Zuge des Fräsens (rechts)

In einem zweiten Arbeitsgang wurden die Flächen mit einer Rodungsfräse in drei Streifen mit jeweils einer Tiefe von 5 cm (flach), 15 cm (mittel) und 30 cm (tief) gefräst und dabei die im Boden verbliebenen Wurzelstöcke zerkleinert und das gemulchte oberirdische Holz (Abb. 2 rechts) in den Boden eingearbeitet. Während durch das tiefe Fräsen die Wurzelstöcke vollständig zerkleinert wurden, ist dies in den beiden flacheren Bearbeitungstiefen nur bis zu einer Tiefe von 5 bzw. 15 cm der Fall.

Abb. 3 Fläche unmittelbar nach dem Fräsen (links) und nach dem Umbruch aus dem Boden abgesiebte Erntereste > 2 mm (rechts)

Nach Einebnung der gefrästen Flächen mittels Kreiselegge erfolgte mit der Einsaat von Silomais (*Zea mays L.*) und Weidelgras (*Lolium perenne L.*) in jeweils dreifacher Wiederholung je Frästiefe die Bestellung als Acker- oder Grünland (Abb. 4). Um die Einflussnahme der mineralischen Düngung auf die C-Dynamik und die mikrobielle Biomasse im Boden gering zu halten, wurden auf allen drei Flächen mit 50 kg N ha^{-1} nur etwa 50% der praxisüblichen N-Düngermenge ausgebracht. Zusätzlich erfolgte eine Gabe von Phosphor, Kalium und Magnesium orientierend am Bedarf, der mittels Gesamtgehaltsanalyse des Bodens bestimmt wurde. Im Folgejahr des Umbruchs erfolgte im Frühjahr 2011 auf allen drei Flächen eine erneute Bodenbearbeitung der Ackerparzellen zur Saatbettvorbereitung für den Mais mittels Kreiselegge gemäß den drei Frästiefen von 5, 15 und 30 cm.

2.3 Bodenbeprobung und Analysen

Für die bodenkundliche Charakterisierung des Ausgangszustandes nach langjähriger KUP Bewirtschaftung wurden im November 2009 auf beiden Flächen am Georgenhof in Tiefen von 0-5, 5-10, 10-15, 15-30 und 30-60 cm und in Wachtum in Tiefen von 0-5, 5-10, 10-15, 15-30 und 30-50 cm mit einem Bohrstock in dreifacher Wiederholung Bodenproben genommen. Zusätzlich wurde die Humusauflage mit dem Boden aufliegenden Totholz in drei 1 x 1 m großen Quadraten beprobt.

Direkt nach dem Fräsen wurde der Boden in Tiefenstufen von 0-5, 5-10, 10-15 und 15-30 cm in der flachen Frästiefe, in 0-15 und 15-30 cm in der mittleren und in 0-30 cm in der tiefen Frästiefe in 3 Wiederholungen je Frästiefe und Tiefenstufe beprobt.

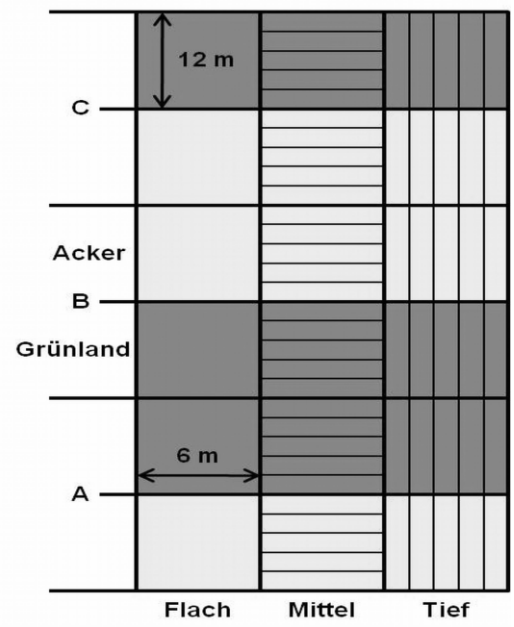

Abb. 4 Versuchsdesign der drei Standorte in einer Streifenblockanlage mit dreifacher Wiederholung (A, B, C) je Frästiefe (Flach, Mittel, Tief) und Nachnutzung (Acker (hellgrau) und Grünland (dunkelgrau))

Ein Jahr nach dem Umbruch erfolgte im Frühjahr 2011 eine zweite Beprobung des Bodens in drei Wiederholungen je Frästiefe, Nachnutzung und Beprobungstiefe. Der Beprobung der Ackerparzellen ging dabei die erneute Bodenbearbeitung zur Saatbettvorbereitung gemäß den drei Frästiefen voraus. Um die groben Erntereste quantitativ mit erfassen zu können, erfolgte die Beprobung des Bodens unmittelbar und ein Jahr nach dem Fräsen mit einem Bohrer mit einem Durchmesser von 10 cm, wobei je Feldwiederholung 2 Proben gezogen und zu einer

Mischprobe vereinigt wurden. Sowohl unmittelbar als auch ein Jahr nach dem Umbruch der KUPs wurden die Erntereste > 2 mm (Abb. 3 rechts) aus den Proben gesiebt und deren C- und N-Gehalte bestimmt.

Um Aussagen über die kurzfristigen Auswirkungen des Umbruchs der KUPs auf die C-Dynamik des Bodens treffen zu können, wurden an allen drei Terminen neben dem gesamten organischen Kohlenstoffgehalt des Mineralbodens, Änderungen in einzelnen C-Fraktionen des Bodens (wasserstabile Aggregatfraktionen, leichte organische Fraktionen und mikrobielle Biomasse) untersucht. Bei der Aggregatfraktionierung durch Nasssiebung erfolgte eine Trennung des Bodens in Makro- (0,25-2 mm) und Mikroaggregate (0,25-0,053 mm) sowie die Ton- und Schlufffraktion mit einer Korngröße < 0,053 mm. Bei der Dichtefraktionierung wurde der Boden mit einer Schwerelösung (Natriumpolywolframat) in die freie und die in Bodenaggregate okkludierte, leichte organische Fraktion unterteilt. Zusätzlich wurde ein Inkubationsversuch im Labor durchgeführt um weitergehende Aussagen über die Abbaudynamik der Erntereste bei unterschiedlicher N-Düngung und Partikelgröße zu erlangen.

3. Ziele der Arbeit

Wie in Kapitel 1 aufgezeigt, sind die Auswirkungen der Rückführung von KUPs in konventionelle landwirtschaftliche Nutzung auf die Kohlenstoffdynamik des Bodens bislang weitgehend ungeklärt. In der vorliegenden Arbeit wurde daher in dem in Kapitel 2 vorgestellten Feldversuch untersucht, wie sich verschiedene Bearbeitungstiefen während der Rückführung langjährig bewirtschafteter KUPs in Acker- oder Grünlandnutzung unmittelbar und 1 Jahr nach dem Umbruch der Flächen auf die Dynamik des organischen Bodenkohlenstoffs auswirken. Infolge der intensiven Bodenbearbeitung während des Umbruchs der KUPs ist von einer erhöhten Mineralisierung der unter KUP akkumulierten organischen Bodensubstanz auszugehen. Daher sollte insbesondere überprüft werden, ob eine reduzierte Bodenbearbeitung und eine nachfolgende Grünland- im Vergleich zur ackerbaulichen Nutzung, das Ausmaß des Abbaus der organischen Substanz vermindert. Dazu wurde bei der Rückführung der KUPs das herkömmlich in der Praxis angewandte, tiefe Bodenbearbeitungsverfahren (Fräsen der Wurzelstöcke bis 30 cm Tiefe) mit denen reduzierter Verfahren (Fräsen bis 15 cm und bis 5 cm Tiefe) verglichen.

In einem ersten Untersuchungsschritt wurde der Ausgangszustand der KUPs vor der letztmaligen Ernte der Bäume charakterisiert, wobei

- die Bestimmung der C-Mengen erfolgte, die in der oberirdischen Biomasse und in der Wurzelbiomasse der Bäume sowie in der Streuauflage und im Mineralgesamtboden gespeichert sind und
- eine Trennung der organischen Bodensubstanz in unterschiedlich mineralisierbare Bodenfraktionen (wasserstabile Aggregatfraktionen, leichte organische Fraktionen und mikrobielle Biomasse) durchgeführt wurde,

um die gesamten Kohlenstoffvorräte langjährig bewirtschafteter KUPs zu ermitteln sowie die Verteilung des Kohlenstoffs in einzelnen Bodenfraktionen zu bestimmen.

Direkt im Anschluss an das Fräsen der Flächen erfolgte die Untersuchung der unmittelbaren Auswirkungen des Umbruchs der KUPs. Dazu wurden

- die Menge und das C/N Verhältnis der Erntereste > 2 mm bestimmt, die während des Umbruchs in den Boden eingearbeitet wurden und

- der Effekt der drei Bearbeitungstiefen auf den Gesamtkohlenstoffgehalt des Mineralbodens sowie auf die Verteilung des organischen Kohlenstoffs in den einzelnen Bodenfraktionen (s.o.) untersucht.

Ausgehend von diesem Zustand direkt nach dem Umbruch wurde im Folgejahr des Umbruchs erneut untersucht, wie sich die drei Bearbeitungstiefen sowie die anschließende Acker– und Grünlandnutzung auf

- die in den Ernteresten > 2 mm gespeicherten C-Mengen sowie deren C/N Verhältnis als Indikator für den Abbaugrad,
- die Menge an Gesamtkohlenstoff des Mineralbodens und
- die Verteilung des organischen Kohlenstoffs in den einzelnen Bodenfraktionen (s.o.) auswirken,

um erste Abschätzungen geben zu können, ob eine reduzierte Bodenbearbeitung und nachfolgende Grünlandnutzung den zu erwartenden Mineralisierungsschub mindern können.

Erste Ergebnisse des Feldversuches zeigten, dass im Zuge der Rückführung der KUPs hohe Mengen an grob zerkleinerten Wurzel- und oberirdischen Ernterückständen, insbesondere in Form von Kronenmaterial, in den Boden eingearbeitet wurden. Die sehr heterogene Einarbeitung der unterschiedlich groß zerkleinerten Erntereste erschwerte jedoch die Untersuchung der Auswirkungen der Erntereste auf die C-Dynamik des Bodens. Um dennoch einen tieferen Einblick in die Abbaudynamik der Erntereste zu erlangen, wurde ein Inkubationsversuch im Labor durchgeführt. Dabei wurden der Einfluss unterschiedlicher Partikelgrößen der Erntereste sowie der Einfluss einer N-Düngung auf die Mineralisation von Kronen- und Wurzelmaterial untersucht.

Ziel des Versuches war es folgende Fragen zu beantworten:

- in welcher Weise beeinflussen die N-Zugabe und die Partikelgröße die Mineralisierung des Kronen- und Wurzelmaterials,
- wird durch die Zufuhr des Kronen- und Wurzelmaterials mineralischer N im Boden immobilisiert und
- wie wirkt sich die Einarbeitung des Kronen- und Wurzelmaterials auf die mikrobielle Biomasse im Boden aus?

4. Carbon in plant biomass and soils of poplar and willow plantations - implications for SOC distribution in different soil fractions after re-conversion to arable land

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Abstract

Aims Effects of final harvest of plantations and re-conversion with different tillage intensities on quantity and distribution of organic matter in different soil fractions were assessed.

Methods A field trial was conducted at two poplar and one willow plantation in northern Germany. Distribution of C in aboveground plant and root biomass and within various soil fractions (light fraction organic matter, water-stable aggregates, microbial biomass) was determined. Directly after re-conversion, which was performed at tillage depths of 5, 15 and 30 cm, C amounts added with coarse harvest residues and changes in soil C fractions were examined.

Results Plantation C stocks decreased in the order soil > aboveground biomass > roots. After re-conversation no change in bulk soil SOC but an increase of labile soil C was observed. Between 16 and 30 t ha^{-1} additional C was determined in the soil fraction of plant residues > 2 mm after re-conversion. Up to 90% SOC of the fine earth fraction was associated with macroaggregates, which increased after re-conversion despite intensive tillage with a rotary cultivator.

Conclusion The duration of the increased macroaggregate associated C directly after soil tillage is a short term effect of the tillage. The influence of tillage depths on soil C-fractions could be observed only in some cases because of the high variability of harvest residues in the field.

4.1 Introduction

The demand for woody biomass has recently led to increased interest in woody biomass production in tree plantations with fast growing tree species such as poplar (*Populus spp*.) and willow hybrids (*Salix spp*.) on former arable land. After 20 to 30 years, the productivity of trees generally decreases and the stands have to be re-established or re-converted to grass or arable land (Grogan and Matthews 2002; Kahle et al. 2010). But until now, the effects of this re-conversion have rarely been examined.

Tree plantations on former arable land lead to a non-tillage management with increased litter amounts and have the potential to increase the soil organic carbon (SOC) in the long term (Jug et al. 1999; Post and Kwon 2000; Kahle et al. 2007; Baum et al. 2009; Nair et al. 2009; Rose-Marie 2012). These investigations focused on the amount of SOC, but neglected quality and allocation of C in different organic matter fractions. Afforestation and absence of tillage generally reduced soil disturbance and increased soil aggregation (Six et al. 2000), light fraction organic matter (LF) and microbial biomass C in soil (Mao and Zeng 2010). In plantations with rotation cycles exceeding 10 years, which is common in plantations producing raw material for industrial use, most C was found to be stored in the aboveground tree biomass and it appears that belowground root biomass constitute an important proportion of C stocks (Singh 1998; Fang et al. 2007; Sartori et al. 2007). But there is still a knowledge gap on belowground biomass carbon stocks of tree plantations and almost all available studies are based on model estimations. During re-conversion, intensive soil tillage is performed for breaking up roots and coarse harvest residues after the final harvest for seedbed preparation.

The incorporation of these residues increased total SOC stocks (Kirschbaum et al. 2008), but the intensive soil tillage destroyed soil aggregates and exposed organic colloids to decomposers (Post and Kwon 2000), leading to an enhanced mineralization of soil organic matter. Considering the two contrasting effects of the re-conversion of tree plantations back to arable land, more information on the impacts on SOC dynamics is needed. Studies have shown that initial C losses are mainly caused by mineralization of the labile SOC pools such as the microbial biomass, macroaggregate associated C and light fraction organic matter (Okore et al. 2007; Yang et al. 2009). This led us to hypothesize that a reduction in tillage intensity reduces C loss during the re-conversion of tree plantations. In the current study, the short-term effects of the re-conversion on SOC stocks and dynamics were investigated on tree plantations with a rotation cycle of 12 years at three sites in northern Germany. The objectives of the study were (1) to examine the changes of soil properties and SOC fractions with depth

under poplar and willow plantations, (2) to quantify the amount of harvest residues remaining in the soil after re-conversion, and (3) to analyse effects of tillage intensity on the distribution of SOC on different soil fractions immediately after re-conversion of tree plantations.

4.2 Material and Methods

4.2.1 Site description

The study was conducted at three experimental sites in northern Germany. At the Georgenhof site (51°27'N, 9°0'O, 320 m a.s.l.), the studies were performed on a willow plantation and an adjacent poplar plantation. Mean annual precipitation and mean annual temperature are 740 mm and 7.9°C, respectively. Soil type is a Stagno-Gleyic Cambisol derived from loess (FAO-WRB, 2006). Soil texture (0-30 cm) at the Georgenhof willow site is a sandy loamy silt (28% sand, 61% silt, 11% clay), at the poplar site a silty loam (19% sand, 64% silt, 17% clay). The poplar plantation at the third site Wachtum (52°47'N, 7°44'O, 22 m a.s.l.) has a mean annual precipitation and temperature of 815 mm and 9.0°C, respectively. Soil type is a deep-ploughed Gleyic Podzol; soil texture is a silty sand (76% sand, 20% silt, 4% clay).

The plantations were established on former arable land in 1987 (Georgenhof) and 1989 (Wachtum) for the testing of fast growing willow (*Salix spp.*) and poplar (*Populus spp.*) clones. From 1998 to the final harvest in 2010, no cutting was carried out at any site, as the plantations were used for demonstrating the production of raw material for the paper industry. The initial plant density at the Georgenhof willow site was 15,385 trees ha^{-1} (1.3 × 0.5 m), at the Georgenhof poplar site 10,000 trees ha^{-1} (1 × 1 m). At the Wachtum poplar site, clones were planted with a spacing between 2.2 × 1.2 m (3788 trees ha^{-1}) and 3 × 1.2 m (2777 trees ha^{-1}). Due to thinning and high plant mortality, the tree density before the final harvest was 1296 trees ha^{-1} at the Georgenhof willow site, 1905 trees ha^{-1} at the Georgenhof poplar site and 1942 trees ha^{-1} at the Wachtum poplar site.

4.2.2 Stand level biomass

For estimating above and belowground biomass of the poplar plantations, tree height and mean diameter at 1.3 m height (dbh) of all trees without the marginal rows were measured by crosswise clipping. The trees were divided into five dbh-classes ranging from 9-24 cm and one tree of each class was selected for destructive sampling. The sample trees were cut at ground level and subdivided into stem until 7 cm diameter and crown. The crown was chaffed

and the chaffs and the stem were weighed in the field to obtain fresh weight. Sub-samples of both compartments were dried at 105°C until a constant weight was reached for determination of the dry matter (DM) content. For the root biomass assessment, a 1.4 × 1.4 m square centred around each sample tree was excavated to a depth of 30 cm. It was assumed that roots of surrounding trees within the sample area compensated for roots of the measured tree that were outside the sampled area. The roots were collected, washed, dried at 60°C, divided into stump, coarse (> 5 mm) and fine (< 5 mm) roots, weighed and ground. Potential regression equations were developed by using the DM of the separate tree compartments (stem, crown, root fractions) as the dependent variable for calculating the aboveground and the root fraction biomass of the stands in relation to the dbh as follows:

$$B = b_0 \times dbh^{b_1}$$

where B is the biomass of the tree compartment or root fraction mass (kg), b_0 and b_1 were parameter estimates and dbh was the diameter (cm) of the stem at 1.3 m height. The dbh value of each tree was fitted into the regression equation for calculating the biomass. The values were summed and converted to a hectare basis. Due to an R^2 of between 0.7 - 0.9 the dbh was solely used as explaining variable for biomass estimation in accordance with Röhle et al. (2009). The aboveground and root biomass of the willows was estimated by the mean tree technique. Three selected trees (stem and shoots), that best represent the mean size of the plantation, were destructive sampled. Fresh weight was determined in the field and DM of chaffed sub-samples in the laboratory. Root biomass was determined as described above. For estimation of total above and belowground biomass the number of tress in the plantation was used to expand the mean tree values to an area basis.

4.2.3 Tree harvesting and soil sampling

The trees were manually harvested in spring 2010 with a chain saw at the willow site and with a harvester at the two poplar sites. The harvester delimbed the trees, so that the entire crown material remained at the poplar sites. For restoring the sites, stumps and harvest residues were first mulched with a wood mulcher. Then this mulched debris, the root stumps and coarse roots were ground and tilled into the soil with a rotary cultivator. This was carried out in three strips, each with a width of 6 m at the two Georgenhof sites and 4 m at Wachtum, with tillage depths of 5 cm (shallow), 15 cm (medium) and 30 cm (deep). Soil was levelled with a rotary

harrow and maize (*Zea mays L.*) and rye grass (*Lolium perenne L.*) were sown in three replicates per tillage depth in strips of 12 m.

In winter 2009/2010, before the final harvest, soil samples were taken at 0-5, 5-10, 10-15, 15-30 and 30-60 cm depth in three replicates per depth and site. Additionally the litter layer and overlying deadwood was sampled from three 1 × 1 m squares per site, oven-dried at 60°C, weighed, ground and analysed for C and N content. Directly after rotary cultivation, the soil was sampled again in three replicates per tillage treatment at 0-5, 5-10, 10-15, and 15-30 cm depth in the shallow, in 0-15 and 15-30 cm in the medium and in 0-30 cm in the deep tillage treatment with a 10 cm diameter corer. Two samples of each depth were combined per replicate. At both dates, bulk density was determined gravimetrically in 5 cm steps, using a steel corer (diameter 4 cm). All soil samples were sieved (< 2 mm). From the samples taken after cultivation, root and aboveground harvest residues > 2 mm were collected from the sieve, washed and dried at 60°C. Sub-samples of harvest residues were dried at 105°C to constant weight for determination of the dry matter content.

4.2.4 Soil analysis

Soil pH was determined in 0.01 M $CaCl_2$ at a soil/solution ratio of 1/2.5. For estimating microbial biomass C (Vance et al. 1987), two portions of 15 g field-moist sieved soil, stored at 4°C until analysis, were extracted with and without $CHCl_3$ fumigation with 40 ml 0.5 M K_2SO_4. Organic C in the extracts was measured after combustion using a Dimatoc 100 automatic analyzer (Dimatec, Essen, Germany). Microbial biomass C was calculated as the difference between fumigated and unfumigated samples using a k_{EC} value of 0.45 (Wu et al. 1990) to account for the non-extractable part.

Water stable aggregate fractions to a depth of 30 cm were determined at both sampling dates by wet sieving, using the method described by John et al. (2005). Dried soil (40ºC) of 100 g (< 2 mm) was separated in two portions of 50 g, soaked in distilled water for 10 min to allow slaking. Each mixture was poured onto a 250 µm sieve, which was moved up and down in water with 50 repetitions, taking care that the screen broke the water surface every time. The fraction > 250 µm was collected, the two mixtures were combined and the sieving was repeated using a 53 µm sieve. Fine particles < 53 µm in the supernatant were precipitated with 0.5 M $AlCl_3$. All size classes were dried at 40°C and ball-milled for C and N analysis. To obtain free light fraction organic matter (fLF), density fractions were obtained in the bulk soil before and after re-conversion according to John et al. (2005). For the soil from the two

Georgenhof sites, 10 g of field-moist soil was placed in a centrifugation tube together with 30 ml sodium-polytungstate (SPT) solution (Sometu, Berlin, Germany) adjusted to a density of 1.8 g cm^{-3}. After shaking the tube gently five times by hand, the solution was allowed to settle for 30 min and centrifuged at 3000 *g* for 30 min. The supernatant with floating particles was vacuum-filtered (0.45 µm) and washed with distilled water to remove SPT. The fLF was dried for 48 h at 40°C and ground with a mortar. For the soil from the Wachtum site, the SPT solution was adjusted to 2 g cm^{-3}. Due to the high sand content of this site, free and aggregate-occluded LF (oLF) was not separated. For this reason, 10 g of field moist soil was placed in a centrifugation tube together with 30 ml SPT and the suspension was shaken for 16 h at 175 rev min^{-1} together with ten glass beads of 5 mm diameter before centrifugation and filtration as described above.

4.2.5 C and N analysis in plant and soil samples

Total C and N of the soil, litter, deadwood, tree samples and harvest residues > 2 mm were determined after drying at 60°C for 24 h by dry combustion (Elementar Vario El, Heraeus, Hanau, Germany). As no significant change in soil bulk density before and after re-conversion was detected, C stocks were calculated on a volume-based method, considering the bulk density of the different soil depths. C stocks of the tree compartments were estimated by multiplying their calculated mass by the mean C concentration. C contents of the aggregate fractions were not corrected for sand content, as analysis of the temporal variation on the individual sites was the primary aim, rather than a comparison between the sites.

4.2.6 Statistical analysis

All results presented are arithmetic means and are expressed on an oven-dry basis. Normality of data was tested with Shapiro-Wilk statistics and homogeneity of variance was assessed with Levene's test. Changes in properties before and after re-conversion were calculated for a cumulative sampling depth of 30 cm by a paired t-test ($P < 0.05$). Differences between the willow and the poplar site Georgenhof were estimated by a t-test ($P < 0.05$). The effect of the tillage treatment was tested by a one-way analysis of variance (ANOVA). Mean comparisons were performed using the Tukey test at $P < 0.05$. All statistical analyses were performed using JMP 8.0 (SAS Inst. Inc.).

4.3 Results

4.3.1 Vertical distribution of soil properties in poplar and willow plantations

At all sites, bulk density in the upper 10 cm was low (Fig. 5a). Soil pH at Georgenhof willow and at Wachtum poplar was strongly acidic, with no clear differences between depths. With an average of 5.5, pH was higher in the upper 10 cm at Georgenhof poplar than in the depths below and in comparison with Georgenhof willow (Fig. 5b). The SOC content declined with depth in all cases. It was always lowest at Georgenhof willow (Fig. 5c) and the decline was less pronounced at Wachtum poplar. The soil C/N ratio remained roughly constant at both Georgenhof sites, but increased with depth to 21 at Wachtum (Fig. 5d).

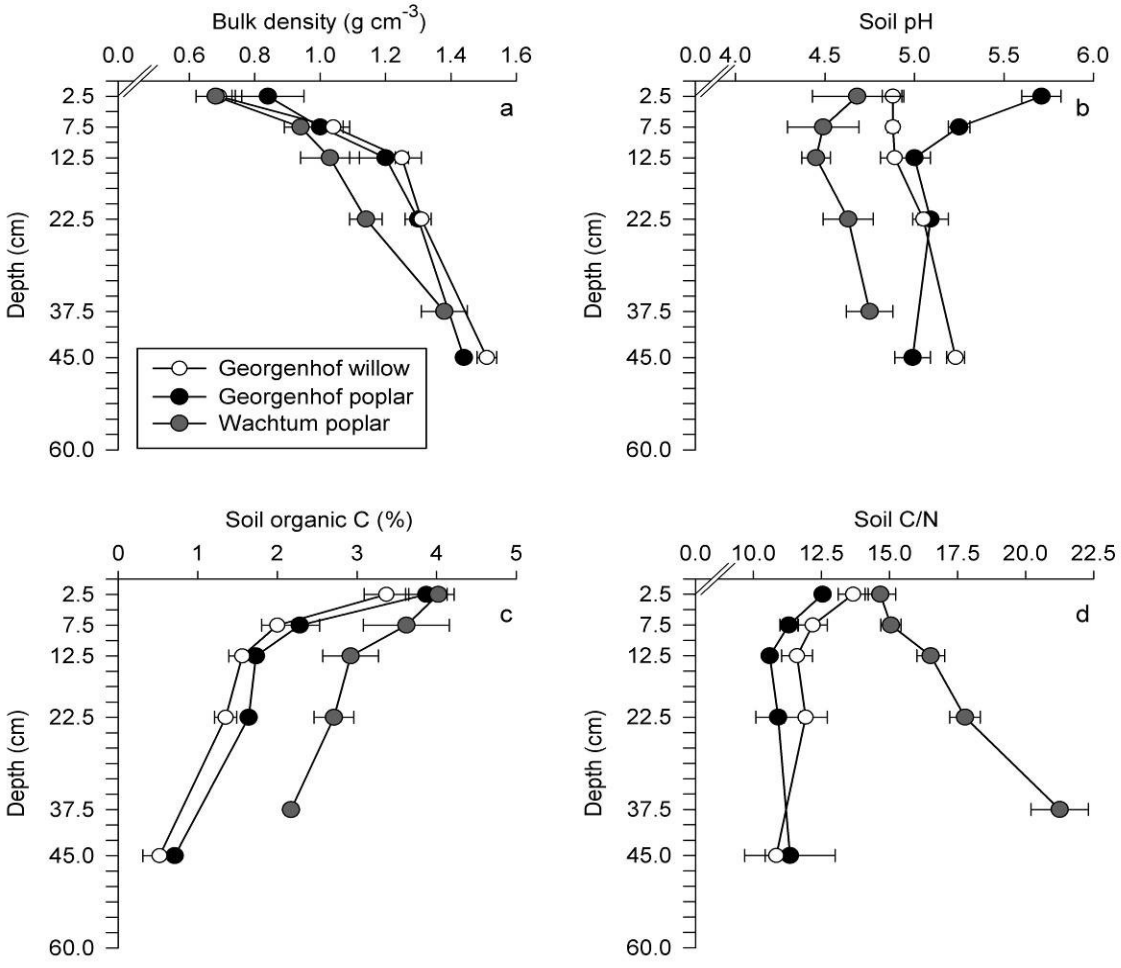

Fig. 5 Mean of (a) bulk density, (b) soil pH, (c) soil organic C content and (d) soil C/N at different depths of the plantations; error bars show standard error (n = 3)

Also the microbial biomass C content generally declined with depth (Fig. 6). At 0-5 cm depth, higher microbial biomass C contents were found at both Georgenhof sites in comparison with Wachtum, whereas the reverse was observed at 20-30 cm depth.

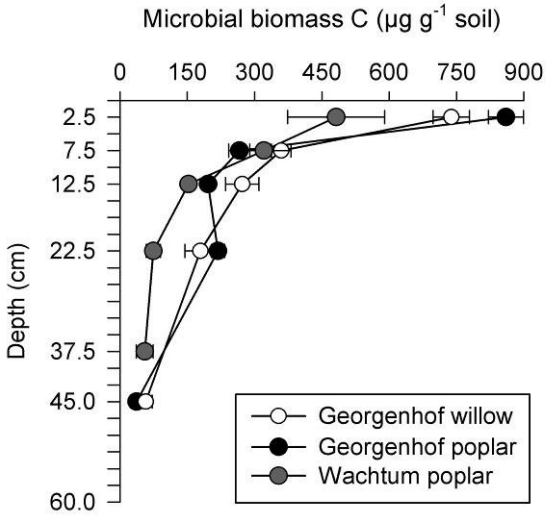

Fig. 6 Mean content of microbial biomass at different depths of the plantations; error bars show standard error (n = 3)

Recovery of soil after aggregate fractionation ranged between 97 and 104%, whereas the proportion of C to SOC was normalized to a 100% recovery. At all sites, aggregate fractionation showed that the C contribution to SOC increased in the order < 53 µm < 250-53 µm < 250-2000 µm (Table 1). The C associated with the 250-2000 µm always decreased with depth. However, at Georgenhof poplar, less C was associated with the two smaller fractions below 10 cm and more with the 250-2000 µm fraction in comparison with Georgenhof willow. At Wachtum, a pronounced increase in the 53-250 µm occurred below 15 cm as the fine sand fraction increased (data not shown). In comparison with the mineral associated C, less C was bound in the fLF fraction at both Georgenhof sites, with an average contribution of 2% to SOC at the poplar and slightly above 3% at the willow site. At Wachtum, LF comprised between 69 to 83% of SOC. In contrast to both poplar sites, fLF decreased with depth at Georgenhof willow (Table 1).

Table 1 Contribution of aggregate size classes and light fraction organic matter to soil organic C at the three plantations

	Contribution to soil organic C (%)			
Depth (cm)	< 53 µm	53-200 µm	250–2000 µm	fLF
Georgenhof willow				
0- 5	2.4	6.6*	91.0*	4.8
5-10	3.6	10.4	86.0	3.6*
10-15	5.6*	13.9*	80.4	3.4*
15-30	9.1*	15.1*	75.9*	1.9
Georgenhof poplar				
0- 5	2.3	12.1	85.6	3.2
5-10	3.3	8.1	88.6	1.9
10-15	4.6	11.0	84.4	0.8
15-30	4.7	11.6	83.6	1.8
Wachtum poplar				
0- 5	3.8	11.9	84.3	82.7†
5-10	3.7	20.2	76.1	81.3†
10-15	4.4	28.9	66.7	69.2†
15-30	5.8	40.4	53.8	83.4†
CV (± %)	16	17	4	30

fLF = free light fraction organic matter; CV = mean coefficient of variation between replicate samples (n = 3); † free and occluded light fraction; * depth-specific significant difference between willow and poplar stands at the site Georgenhof ($P < 0.05$)

4.3.2 Carbon stocks of plant biomass and soil

The C stocks of the aboveground biomass were 15 t ha^{-1} at Georgenhof willow, 71 t ha^{-1} at Georgenhof poplar and 50 t ha^{-1} at Wachtum (Table 2). The C stocks of the root biomass decreased in the order stump roots > coarse roots > fine roots. The organic surface layer was characterized by slightly decomposed litter at all sites, with absence of a humified layer. In the organic surface layer, more than 2 t C ha^{-1} was accumulated at Georgenhof poplar, but only 1 t C ha^{-1} at Georgenhof willow. The SOC stocks down to 30 cm depth contributed 79, 47 and 62% to total C stocks at Georgenhof willow, Georgenhof poplar and Wachtum, respectively. The C/N ratio of the root fractions decreased in the order stump roots > coarse roots > fine roots at all sites, with a higher C/N for the poplar stump roots than for the willow stump roots (Table 3).

Table 2 Stocks of organic C in different plant and soil compartments

	Georgenhof willow	Georgenhof poplar	Wachtum poplar
		Organic C (t ha^{-1})	
Crown		13.7	11.2
Stem	15.3[§]	56.7	38.8
Stump roots	0.6	4.6	3.6
Coarse roots > 5 mm	0.4	2.8	3.2
Fine roots < 5 mm	0.1	1.2	0.7
Dead wood	0.4* (0.1)	0.9 (0.1)	0.8 (0.4)
Litter	0.8* (0.1)	1.4 (0.1)	1.7 (0.6)
Soil (0-30 cm)	58.5 (10.3)	68.9 (3.9)	92.1 (15.9)
Soil (30-60 cm)	15.8* (6.4)	31.8 (3.4)	60.1 (0.7)[§§]
Sum	91.9	182.0	212.2

§ Stem + shoots, §§ 30-50 cm; (in brackets) standard deviation;

* significant difference between willow and poplar stands at the site Georgenhof ($P < 0.05$)

4.3.3 Changes in C fractions after re-conversion

Compared with the mean C/N ratio of all three root fractions that of the harvest residues decreased 3 to 4 fold at both poplar sites after re-conversion (Table 3). No significant change in C stocks of the mineral fine soil occurred shortly after re-conversion at 0-30 cm depth at any site or tillage treatment. Harvest residue C > 2 mm exceeded only the stocks of root C before re-conversion by 16 t C ha^{-1} at Georgenhof willow, 13 t C ha^{-1} at Georgenhof poplar and 16 t C ha^{-1} at Wachtum, averaging the three tillage depths (Table 4). More than 90% of the harvest residue C accumulated in the upper 15 cm in the shallow tillage treatment at all sites. At Georgenhof willow and at Wachtum poplar, 60% of harvest residue C was found at 0-15 cm depth and 40% at 15-30 cm depth in the medium tillage treatment. The respective values were 80 and 20% at Georgenhof poplar (data not shown).

Table 3 C/N ratio of dead wood, litter, crown, root fractions, weighted mean of all root fractions of the plantations before re-conversion and C/N ratio of harvest residues (> 2 mm) after re-conversion averaged for all three tillage treatments

	Georgenhof willow	Georgenhof poplar	Wachtum poplar
	C/N		
Dead wood	51 (6.3)	49 (6.8)	49 (9.6)
Litter	24 (1.2)	23 (1.3)	22 (2.6)
Crown	302§ (76.5)	292 (61.8)	n.d.
Stump roots	203 (29.5)	434 (37.5)	503 (68.8)
Coarse roots > 5 mm	87 (8.9)	94 (11.3)	107 (15.7)
Fine roots < 5 mm	55 (9.9)	62 (5.6)	75 (17.7)
Mean of roots	147 (22.1)	262* (1.7)	288* (3.8)
Harvest residues	123 (41.3)	80 (16.7)	66 (11.2)

§ Stem + shoots; (in brackets) standard deviation; * significant difference between mean of roots of the plantations and harvest residues after re-conversion ($P < 0.05$)

Stocks of microbial biomass C increased at all sites after re-conversion, but only significantly for the shallow tillage treatment at Georgenhof poplar and for the deep tillage treatment at Wachtum. The contribution of fLF-C to total SOC increased at both Georgenhof sites after re-conversion. At Georgenhof willow, significantly less C was associated with fLF in the deep than in the shallow tillage treatment. At Georgenhof poplar, less fLF-C was detected in the

shallow and medium tillage treatments compared to the willow site. At Wachtum poplar, the increase in the proportion of fLF-C was not significant after re-conversion (Table 4).

Table 4 Stocks of microbial biomass C, contribution of light fraction organic matter C to total soil organic C, organic C stocks of the mineral fine soil (0 – 30 cm), roots of the plantations before re-conversion and harvest residues (> 2 mm) of the three tillage treatments after re-conversion

	Microbial biomass C	fLF-C	Soil organic C	Root and Harvest residue C
	($kg\ ha^{-1}$)	(% SOC)	($t\ ha^{-1}$)	
Georgenhof willow				
Plantation	920	2.9*	60*	1.1*
Shallow tillage	1260 a	13.0§ a*	65 a	15.5§ a
Medium tillage	1460 a	10.3§ ab*	64 a	18.8§ a
Deep tillage	1990 a	7.5 b	79 a	17.5§ a
Georgenhof poplar				
Plantation	1020	1.9	71	8.6
Shallow tillage	1950§ a	8.0§ a	71 a	17.0§ a
Medium tillage	1620 a	7.4§ a	66 a	19.7§ a
Deep tillage	1770 a	9.0§ a	73 a	27.2§ a
Wachtum poplar				
Plantation	480	80.6†	95	7.5
Shallow tillage	1080 a	85.1† a	89 a	20.9§ a
Medium tillage	980 a	89.9† a	96 a	12.9 a
Deep tillage	1620§ a	91.5† a	103 a	37.0§ a
CV (± %)	30	30	19	45

SOC = soil organic C; fLF = free light fraction organic matter; CV = mean coefficient of variation between replicate samples (n = 3); † free and occluded light fraction; § significant difference between the tillage treatment and the initial value of the tree plantations; different letters indicate a significant difference among the three tillage treatments; * significant difference between willow and poplar stands at the site Georgenhof ($P < 0.05$)

Despite soil tillage during re-conversion, aggregate fractionation revealed a roughly 7% increase of C associated with the 250-2000 µm fraction at all treatments at Georgenhof poplar, accompanied by a corresponding decrease in C associated with the 53-250 µm. In the medium tillage treatment at Georgenhof willow, the proportion of C in the 250-2000 µm fraction increased by 9% and decreased in the smaller fractions (Table 5). As the C content of the particular fraction remained constant, the changes were only caused by the fraction mass. At Wachtum poplar, no differences in aggregate fractions were found after re-conversion. The C distribution in the fractions across all sites was not affected by the different tillage treatments (Table 5).

Table 5 Contribution of the aggregate size fractions in the mineral fine soil (0 – 30 cm) to total soil organic C of the plantations before and in the three tillage treatments after re-conversion

	Contribution to soil organic C (%)		
	< 53 µm	53-250 µm	250-2000 µm
Georgenhof willow			
Plantation	5.3*	11.3	83.4
Shallow tillage	3.4 a	10.1 a*	86.6 a*
Medium tillage	2.8[§] a	4.9[§] a	92.3[§] a
Deep tillage	3.1 a	6.7 a*	90.1 a
Georgenhof poplar			
Plantation	3.7	11.0	85.3
Shallow tillage	3.6 a	6.2[§] a	90.2[§] a
Medium tillage	3.2 a	4.2[§] a	92.6[§] a
Deep tillage	2.9 a	4.0[§] a	93.2[§] a
Wachtum poplar			
Plantation	4.7	28.2	67.1
Shallow tillage	8.3 a	29.5 a	62.1 a
Medium tillage	8.0 a	22.8 a	69.3 a
Deep tillage	5.5 a	19.4 a	75.2 a
CV (± %)	26	30	6

CV = mean coefficient of variation between replicate samples (n = 3); [§] significant difference between the tillage treatment and the initial value of the tree plantations; different letters indicate a significant difference among the three tillage treatments; * significant difference between willow and poplar stands at the site Georgenhof ($P < 0.05$)

4.4 Discussion

4.4.1 Vertical distribution of soil properties under plantations

After more than 20 years' no-tillage management the soil physical, chemical and biological properties developed clear depth gradients. Land-use change to tree plantation management increased organic matter input, root growth and bioturbation, leading to a decrease in bulk density of the top soil, as reported by Kahle et al. (2007) and Mao and Zeng (2010). At 0-10 cm depth, the lower pH under willow than under poplar clones may be a species effect (Kahle et al. 2007), although differences in site properties cannot be excluded. At Georgenhof poplar, a deeper rooting depth was observed in comparison with Georgenhof willow, resulting in stronger translocation of alkaline cations by the litterfall into the topsoil. At Wachtum, the depth gradient of SOC was less pronounced and the C/N ratio increased with increasing depth, as peat was deep ploughed in long before the plantation was established.

The high microbial biomass C content in the upper 5 cm at all sites is in accordance with studies of Makeschin (1994), Pellegrino et al. (2011) and Mao and Zeng (2010), who reported that afforestation and no-tillage resulted in larger quantities of leaf and root litter supply to the top layer than arable management. Under fast growing tree-plantations, the majority of fine roots colonize the upper 10 cm (Afas et al. 2008; Heinsoo et al. 2009) providing fresh organic matter and easy available root exudates for soil microorganisms. Different microbial biomass C contents in the upper 5 cm between the two Georgenhof sites can be attributed to higher litter input and higher soil pH at the poplar site. However, this contrasts the results of Schmitt et al. (2010), who reported higher microbial biomass C contents under willow than under poplar clones. They explained this difference by higher degradability of willow leaves, which often have a lower C/N ratio and a lower lignin content than poplar leaves (Chauvet 1987). In the current study, the C/N ratio of the litter layer did not differ between Georgenhof poplar and Georgenhof willow site.

4.4.2 C distribution in aggregate fractions under plantations

The contribution of aggregate fraction C to SOC decreased with decreasing aggregate size because larger aggregates are composed of small aggregates plus organic bindings (Elliott et al. 1991; Puget et al. 2000; Six et al. 2000). Another reason is that soils with permanent vegetation generally contain more macroaggregates than frequently tilled soils (Six et al. 2000; Christensen 2001; DeGryze et al. 2004). Afforestation with poplar for 10 years has

been found to increase soil macro-aggregation to a level similar to that of a native forest (DeGryze et al. 2004). In contrast to the Georgenhof sites, in the sandy Wachtum soil, the 250-2000 and 53-250 µm mainly comprise mineral complexes and uncomplexed organic matter of the sand size fraction. In permanently vegetated soils, uncomplexed organic matter can significantly contribute to the organic C content of sand-sized separates (Christensen 2001). Furthermore, it is known that the amount of organic matter associated with the sand fraction is small (Christensen 2001) and that soils poor in silt and clay have a small capacity for C stabilization on mineral surfaces (Baldock and Skjemstad 2000). The high proportion of C associated with the fLF at this site is with this consistent.

4.4.3 Distribution of C stocks in long-term managed tree plantations

The C stocks of 70 t ha^{-1} for the aboveground biomass and 8.6 t ha^{-1} for the roots at Georgenhof poplar are in range with the results of Fang et al. (2007) who reported 72 t C ha^{-1} for the aboveground biomass and 9.5 t C ha^{-1} for the roots. However, their study was conducted in an 10-year-old poplar plantation with a planting density of 1111 plants ha^{-1}. This is almost half of the plant density of the Georgenhof poplar site (1905 plants ha^{-1}) where aboveground biomass has grown for 12-years from 23 year-old root stumps. A higher mean temperature (14°C) at the study site of Fang et al. (2007) may be reason for the higher growth rate compared to this study. In the study of Sartori et al. (2007), aboveground biomass accumulated 62% of total C and coarse roots > 5 mm 12% in an 11-year-old poplar plantation. At Georgenhof poplar and Wachtum poplar, 39 and 24% of total C were stored in the aboveground biomass as well as 2.5 and 1.7% C in the coarse roots, respectively. Crow and Houston (2004) observed that more than 70% of poplar and willow roots were < 5 mm in diameter at root stump ages of between 3 - 9 years. In contrast, the more than 20-year-old root stumps of the current study had more coarse roots. Generally, data for root biomass vary widely in the literature due to different sampling methods as well as plantation characteristics such as age, tree density, clones, rotation cycles and soil characteristics, making a comparison between studies difficult (Vogt et al. 1998; Nair et al. 2009). A loss of fine root mass might have occurred during root excavation and further sample preparation, leading to an underestimation of the fine root biomass. An annual amount of between 3 - 4 t leaf biomass ha^{-1} was reported for an 18-year-old poplar plantation (Meiresonne et al. 2006), equivalent to approximately 1.5 - 2 t C ha^{-1} a^{-1}, deposited as litter on the soil surface. This amount is in accordance with the C stocks of 1.4 and 1.7 t ha^{-1} in the litter layer at Georgenhof poplar and

Wachtum poplar. In summary, between 60 and 102 t C ha^{-1} are stored in the litter layer, root biomass and soil down to 30 cm and will be affected by the deep tillage treatment during re-conversion of the plantations.

4.4.4 Short-term effects of soil tillage and harvest residue input on soil C fractions

Directly after re-conversion, C stocks of harvest residues increased over all tillage treatments by roughly 14 t C ha^{-1} at the two poplar sites. This increase was mainly caused by incorporation of 12 t C ha^{-1} with crown material, remaining after delimbing of the trees and the tree stumps. At Georgenhof willow, little aboveground biomass remained due to motor-manual harvesting. The differences between C stock in the former willow plantation, which consisted of only roots, and the harvest residues after re-conversion were possibly caused by different sampling methods: excavation was used before harvest and coring after harvest, which may have resulted in a large underestimation of the willow root mass. Woody residues left after harvest in native forests temporarily increased C in the soil by up to 18% for 4 to 18 years (Johnson and Curtis 2001). Consequently, woody harvest residues may be able to contribute to the formation of soil organic matter, mitigating C losses after re-conversion.

At both poplar sites, the C/N ratio of the harvest residues decreased after re-conversion in comparison with the weighted mean of C/N ratio in the three root fractions of the former plantations, despite the incorporation of large amounts of crown material with a high C/N ratio. This observation was caused by the underestimation of the fine root biomass with a lower C/N ratio or of the coarse harvest residues (> 10 cm diameter) with a wide C/N ratio. At the Georgenhof willow site, the C/N ratio of root and harvest residues differed only slightly before and after re-conversion, as only little aboveground biomass remained after harvest.

The SOC associated fLF is considered to be mostly determined by the C input (Six et al. 1998). For this reason, the increased amounts of fLF-C after re-conversion reflects the large input of C with chopped root and aboveground harvest residues at both Georgenhof sites. At the willow site, more fLF-C was determined after re-conversion in the shallow and medium tillage treatment in comparison with the poplar site, despite similar yields of root and harvest residue C. However, more fLF-C was already found in the upper 15 cm at the willow site before re-conversion, additionally explaining the higher amounts of fLF-C in the shallow than in the deep tillage treatment. fLF represents a very labile SOC pool and soil tillage during subsequent arable use increase C-effluxes from this fraction (Okore et al. 2007; Yang et al. 2009).

A decrease of macroaggregates directly after re-conversion was assumed, as soil physical disturbance generally induces a loss of C-rich macroaggregates (250-2000 µm) and the release of relatively stable microaggregates (Six et al. 1999). In contrast to this assumption, an increase of C associated with macroaggregates was observed at both Georgenhof sites after tillage, presumably caused by the incorporation and binding of microaggregates by the harvest residues. As reflected by the increase in fLF-C after re-conversion, parts of the harvest residues were shredded to particles < 2 mm diameter during tillage. Fresh organic residues provide a C source for microbial activity and the production of microbial-derived binding agents induces the formation of macroaggregates (Six et al. 1999; DeGryze et al. 2005; Cosentino et al. 2006). An increase of microbial biomass C was detected after tillage, but no significant correlation between macroaggregates and microbial biomass C was found. It is assumed that the microbial biomass will decrease again when labile sources of the incorporated harvest residues and easily available C and N sources in the soil are exhausted.

4.5 Conclusions

The input of crown material and tree stumps after the final harvest increased total SOC stocks. However, these quantities of harvest residues will only appear in plantations that have prolonged rotation periods. Re-conversion did not affect SOC of the bulk soil, which was not expected in such a short time, but increased microbial biomass C and fLF-C. The increase of C associated with macroaggregates after re-conversion showed that freshly supplied organic matter increased macroaggregate formation. However, the duration of this effect is not known as intensive soil tillage during subsequent arable use may disrupt macroaggregates again, enhancing C turnover. The incorporation of the harvest residues may mitigate C losses with progressive decomposition as residue carbon enters the soil C-pool. Periodical sampling during the following years may give deeper insight into the SOC-dynamics after re-conversion. No influence of tillage intensity for re-conversion was detected on SOC stocks, suggesting that shallow tillage with a rotary cultivator is sufficient. However, it is not known whether shallow tillage is sufficient for preventing regeneration of trees from chopped stump roots. More information is also necessary on how the accumulation of harvest residues with high C/N ratios in the surface soil affect subsequent crop growth.

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5. Dynamics of soil organic carbon fractions one year after the re-conversion of poplar and willow plantations to arable use and grassland

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Abstract

A field trial was conducted at two former fast growing poplar plantations and one willow plantation in northern Germany to study the effects of the re-conversion of the plantations back to agricultural use on soil organic carbon (SOC) dynamics. Re-conversion was performed at tillage depths of 5, 15 and 30 cm and two different land use systems, grassland and maize cropping, were established. Directly after re-conversion and again one year after re-conversion, bulk soil C, distribution of C within various soil fractions (microbial biomass, water-stable aggregates, free and occluded light fraction organic matter) and C amounts added with coarse harvest residues were determined at 0-30 cm soil depths. After re-conversion, the amount of C stored in the harvest residues was 17 to 39 t C ha^{-1}. One year after re-conversion, it had declined by between 7 and 26 t C ha^{-1}. Nevertheless, C of the bulk soil did not change, but a decrease of microbial biomass C, macroaggregate (250-2000 μm) C and free light fraction organic matter indicate a loss of important fractions of soil organic C. Low microbial biomass C contents and microbial biomass C to SOC ratios in the deep tillage treatments suggest a retarded residue decomposition. Occluded light fraction organic matter tended to be greater in deep tillage treatments. More C was found in macroaggregates and the occluded light fraction under grassland use than under arable use one year after re-conversion in loamy soils. Therefore, deep tillage during re-conversion and subsequent grassland use can potentially mitigate C losses after re-conversion of tree plantations.

5.1 Introduction

Producing woody biomass as renewable raw material or an energy source in plantations with fast growing trees such as poplars (Populus spp.) or willow hybrids (Salix spp.) has become more and more popular. Such tree plantations on former arable land do not require tillage and have the potential to increase the soil organic carbon (SOC) in the long term (Nair et al., 2009; Kahle et al., 2010; Mao et al., 2010). After 20 to 30 years of plantation, the productivity of the trees generally decreases and the plantation has to be newly established or can be restored to either grass or arable production (Grogan and Matthews, 2002; Kahle et al., 2010). Until now, the effects of this re-conversion have rarely been examined, but more information on the impact of re-conversion on SOC dynamics is needed to quantify the C sequestration potential of fast growing tree plantations over a whole management cycle.

During re-conversion, intensive soil tillage is performed to break up roots and coarse harvest residues, affecting SOC in two contrasting ways: (1) The intensive soil tillage destroys soil aggregates and exposes organic colloids to decomposers (Post and Kwon, 2000), thus leading to an enhanced mineralization of soil organic matter. (2) The incorporation of harvest residues increases total soil C-stocks (Johnson and Curtis, 2001) and may mitigate SOC losses with progressive residue decomposition (Sanchez et al., 2007).

SOC losses after tillage events of former no-tilled soils are mainly caused by mineralization of labile SOC pools such as the macroaggregate-associated C, light fraction and particulate organic matter (Puget et al., 2000; Six et al., 2000; Chen et al., 2009). This has been reported after conversion of forest ecosystems into arable use by Motavalli et al. (2000) and Okore et al. (2007). In contrast, Abiven et al., (2009) and Chivenge et al., (2011) reported that the incorporation of low quality crop residues with CN ratios up to 41 improved aggregate stability and C-sequestration in agricultural soils, but little is known about the impact of incorporated woody harvest residues on soil aggregation with even lower qualities. Common methods applied to try and reduce organic matter decomposition are to reduce the tillage depth (Kushwaha et al., 2001; Conant et al., 2007) or to cultivate perennial crops or grassland (Guo and Gifford, 2002; Grandy and Robertson, 2007). Tillage depth influences residue incorporation into soil profiles, thus affecting decomposition dynamics (Olchin et al., 2008). Residues will decompose more rapidly when incorporated uniformly throughout the soil profile during deep tillage, due to a better contact with the soil (Balesdent et al., 2000). In contrast, Olchin et al. (2008) suggested a slower decomposition of residues deeper in the profile, originating from less favourable conditions for the microorganisms.

In the current study, a field trial at three former tree plantations in northern Germany was conducted to investigate whether reduced tillage intensity during the re-conversion and subsequent grassland use compared to arable use would reduce mineralization of organic C. The specific objectives were elucidate the effects of three different tillage depths and subsequent land use on (1) total organic C stocks of the bulk soil, (2) on labile soil organic C pools and (3) on the amount of C stored in the incorporated harvest residues one year after re-conversion of the tree plantations.

5.2 Material and Methods

5.2.1 Site Description

The study was conducted at three experimental sites in northern Germany. At the site Georgenhof (51°27'N, 9°0'O, 320 m a.s.l.), the experiments were performed on a willow plantation and an adjacent poplar plantation. Mean annual precipitation and mean annual temperature are 740 mm and 7.9°C, respectively. Soil type is a Stagno-Gleyic Cambisol derived from loess (FAO-WRB, 2006). Soil texture (0-30 cm) at the Georgenhof willow site is sandy loamy silt (28% sand, 61% silt, 11% clay), at the poplar site a silty loam (19% sand, 64% silt, 17% clay). The poplar plantation at the third site Wachtum (52°47'N, 7°44'O, 22 m a.s.l.) has a mean annual precipitation and temperature of 815 mm and 9.0°C, respectively. Soil type is a deep-ploughed Gleyic Podzol; soil texture is a silty sand (76% sand, 20% silt, 4% clay). The plantations were established on former agricultural land in 1987 (Georgenhof) and 1989 (Wachtum). From 1998 to the time of final harvest in spring 2010, no cutting was carried out at any of the sites, as the plantations were managed for raw material use.

5.2.2 Tree harvesting and soil sampling

The trees were manually harvested in spring 2010 with a chain saw at the willow site and with a harvester at the two poplar sites. The harvester delimbed the trees, so that the entire crown material remained at the poplar sites. For restoring the sites, tree stumps and harvest residues were first mulched with a wood mulcher, before the mulched debris, root stumps and coarse roots were ground and tilled with a rotary cultivator into soil. This was carried out in three strips, each with a width of 6 m at the two Georgenhof sites and 4 m at Wachtum, with tillage depths of 5 cm (shallow), 15 cm (medium) and 30 cm (deep), respectively. Soil was levelled

with a rotary harrow and maize (*Zea mays L.*) and rye grass (*Lolium perenne L.*) were sown in three replicates per tillage depth in strips of 12 m.

Directly after rotary harrowing, the soil was sampled in three replicates per tillage treatment and again one year after re-conversion in three replicates per tillage treatment and land use at 0-5, 5-10, 10-15, and 15-30 cm depth in the shallow, at 0-15 and 15-30 cm in the medium and at 0-30 cm in the deep tillage treatment with a 10 cm diameter corer. Before the sampling one year after re-conversion, soil of the arable use was tilled with a rotary harrow according to the three different tillage depths. Two samples of each depth were combined per replicate. At both dates, bulk density was determined gravimetrically in 5 cm steps, using a steel corer (diameter 4 cm). All soil samples were sieved (< 2 mm) and harvest residues > 2 mm were collected from the sieve, washed and dried at 60°C. Sub-samples of harvest residues were dried at 105°C to constant weight for determination of the dry matter content.

5.2.3 Soil analysis

Soil pH was determined in 0.01 M $CaCl_2$ at a soil/solution ratio of 1/2.5. For estimating microbial biomass C (Vance *et al.*, 1987), two portions of 15 g field-moist sieved soil, stored at 4°C until analysis, were extracted with and without $CHCl_3$ fumigation with 60 mL 0.5 M K_2SO_4. Organic C and total N in the extracts were measured after combustion using a Dimatoc 100 + Dima-N automatic analyzer (Dimatec, Essen, Germany). Microbial biomass C and N were calculated as the difference between fumigated and non-fumigated samples using a k_{EC} value of 0.45 (Wu *et al.,* 1990) and a k_{EN} value of 0.54 (Brookes *et al.*, 1985) to account for the non-extractable part.

Water stable aggregate fractions were determined at both sampling dates by wet sieving, using the method described by John *et al.* (2005). As a high proportion of macroaggregates was expected, dried soil (40ºC) of 100 g (< 2 mm) was separated into two portions of 50 g and soaked in distilled water for 10 min to allow slaking. Each mixture was poured onto a 250 µm sieve, which was moved up and down in water with 50 repetitions, taking care that the screen broke the water surface every time. The fraction > 250 µm was collected, the two mixtures were combined and the sieving was repeated using a 53 µm sieve. Fine particles < 53 µm in the supernatant were precipitated with 0.5 M $AlCl_3$. All size classes were dried at 40°C and ball-milled for C and N analysis.

With density fractionation according to John *et al.* (2005), the mineral-associated heavy SOC was separated from the free light fraction organic C located between aggregates (fLF-C)

and the occluded light fraction organic C (oLF-C), released upon aggregate disruption. To obtain fLF from the two Georgenhof sites, 10 g of field-moist soil was placed in a centrifugation tube together with 30 mL sodium-polytungstate (SPT) solution (Sometu, Berlin, Germany) adjusted to a density of 1.8 g/cm^3. After shaking the tube gently five times by hand, the solution was allowed to settle for 30 min and centrifuged at 3000 *g* for 30 min. The supernatant with floating particles was vacuum-filtered (0.45 µm) and washed with distilled water to remove SPT. The pellet remaining in the centrifugation tube was dispersed with 30 mL of SPT using a test tube shaker and 10 glass beads with a diameter of 5 mm were added. The solution was shaken for 16 h at 175 rotations per minute to crack the soil aggregates before centrifugation and filtration as described above to gain oLF. For the soil from the Wachtum site, the SPT solution was adjusted to 2 g/cm^3. Due to the high sand content of this site, free and occluded LF was not separated. For this reason, 10 g of field moist soil was placed in a centrifugation tube together with 30 mL SPT and the suspension was shaken for 16 h at 175 rev/min together with ten glass beads of 5 mm diameter, before centrifugation and filtration as described above. The fractions were dried for 48 h at 40°C and ground with a mortar.

5.2.4 C and N analysis

Total C and N of the bulk soil, soil fractions and harvest residues > 2 mm were determined after drying for 24 h at 60°C by dry combustion (Elementar Vario El, Heraeus, Hanau, Germany). As soil bulk density changed between sampling dates, C stocks were calculated for an equivalent mass of dry soil (Ellert & Bettany, 1995), averaged across all treatments per site. C contents of the aggregate fractions were not corrected for sand content, as analysis of the temporal variation on the individual sites was the primary aim, rather than a comparison between the sites.

5.2.5 Statistical analysis

All results presented are arithmetic means and expressed on oven-dry basis. Normality of data was tested with Shapiro-Wilk statistics and homogeneity of variance was assessed with Levene's test. Changes in properties directly and one year after re-conversion were conducted for a cumulative sampling depth of 30 cm by a paired t-test ($P < 0.05$). The effect of the tillage treatment was tested by a one-way analysis of variance (ANOVA) at both sampling

dates. Mean comparisons were performed using the Tukey test at $P < 0.05$. Differences in properties between arable use and grassland one year after re-conversion were calculated using a t-test ($P < 0.05$). All statistical analyses were performed using JMP 9.0 (SAS Inst. Inc.).

5.3 Results

5.3.1 Soil properties of the study sites

Soil pH was strongly acidic directly after re-conversion at Georgenhof willow and at Wachtum poplar; it slightly increased one year after re-conversion at Georgenhof willow, whereas pH remained constant at Wachtum. A higher, but rarely significant increase of pH occurred at Georgenhof one year after the incorporation of the harvest residues. SOC accounted for 20 mg C g^{-1} at both Georgenhof sites directly after re-conversion and barley changed within one year. The previous deep ploughing of the sandy Podzol at Wachtum caused SOC contents of roughly 30 mg C g^{-1} and high soil C/N ratios, which remained constant between both sampling dates across all treatments and sites (Table 6).

5.3.2 Carbon stocks of soil and harvest residues

Directly after re-conversion, average C stocks of the mineral fine soil were 80 t ha^{-1} at both Georgenhof sites and 111 t ha^{-1} at Wachtum (Table 7). Only at shallow tilled Georgenhof poplar under arable use did the C stock of the mineral fine soil decline by 15 t ha^{-1} after one year.

On average 20, 25 and 34 t C ha^{-1} were incorporated into soil with the harvest residues > 2 mm during re-conversion at Georgenhof willow, Georgenhof poplar and Wachtum, respectively (Table 7). Harvest residue C stocks distinctly decreased within one year but only significantly at shallow tilled Georgenhof poplar under arable use. At Georgenhof willow, harvest residue C stocks were lower in the shallow tillage treatment under both land use types than in the deep tillage treatments after one year. Directly after conversion, the C/N ratio of the harvest residues >2 mm, averaged for the three tillage treatments, was higher for the willow residues than for the poplar residues (Table 7). The C/N ratio decreased within one year in most treatments at Georgenhof willow and at Wachtum, but partly increased at

Georgenhof poplar. The C/N ratios were not affected by tillage treatment and tended to be higher under grassland than under arable land use at all sites.

5.3.3 Microbial biomass

Microbial biomass C accounted for between 1000 and 2000 kg ha^{-1} across all sites after re-conversion and decreased on average by 800 kg ha^{-1} at both Georgenhof sites and by 400 kg ha^{-1} at Wachtum (Table 8). The microbial biomass C/N ratio was 5.6 on average for both Georgenhof sites directly after re-conversion and increased to ratios > 7. In contrast, the mean initial microbial biomass C/N ratio at Wachtum of 9 decreased after one year. Neither microbial biomass C nor the microbial biomass C/N ratio showed strong differences between tillage treatments and land use types one year after re-conversion at any of the sites. The microbial biomass C to SOC ratio decreased one year after re-conversion < 2 at both Georgenhof sites and even < 1 at Wachtum. At Georgenhof willow under arable use and at Wachtum poplar under grassland use, the microbial biomass C to SOC ratio was lower in the deep than in the medium tilled plots. At Wachtum, the microbial biomass C to SOC ratio was lower in the shallow and medium tilled treatments under arable in comparison with those under grassland use.

Table 6 Soil pH, contents of soil organic C and the soil C/N ratio in the upper soil layer (0-30 cm) of three sites directly after re-conversion with three tillage treatments and one year after re-conversion as arable and grassland

	Soil pH			Soil organic C (mg/g soil)			Soil C/N		
	years after conversion			years after conversion			years after conversion		
		Arable	Grassland		Arable	Grassland		Arable	Grassland
	0	1	1	0	1	1	0	1	1
Georgenhof willow									
Shallow tillage	5.0 a	5.2 a*	5.4 a*	20 a	22 a	22 a	13.6 a	13.6 a	14.0 a
Medium tillage	5.0 a	5.2 a*	5.3 a*	20 a	22 a	20 a	14.4 a	14.6 a	13.6 a
Deep tillage	5.1 a	5.2 a	5.3 a*	22 a	18 a	22 a	15.0 a	13.7 a	14.7 a
Georgenhof poplar									
Shallow tillage	5.3 a	5.6 a*	5.5 b	22 a	18 a*	20 a	12.2 a	12.0 a	11.9 a
Medium tillage	5.3 a	5.6 a	5.4 b	21 a	21 a	19 a	11.6 a	12.4 a	12.0 a
Deep tillage	5.4 a	5.9 a	5.7 a	23 a	21 a	20 a	12.1 a	12.5 a	12.0 a
Wachtum poplar									
Shallow tillage	4.9 a	4.9 a	4.9 a	29 a	27 a	28 a	16.9 a	17.1 a	18.1 a
Medium tillage	4.9 a	4.9 a	4.9 a	30 a	32 a	26 a	18.0 a	17.3 a	17.7 a
Deep tillage	4.9 a	4.9 a	4.9 a	31 a	34 a	30 a	17.7 a	18.5 a	16.9 a
CV (± %)	2	2	1	17	27	19	13	10	9

CV = mean coefficient of variation between replicate samples (n = 3); different letters indicate a significant difference between tillage treatments;

* significant difference between years ($P < 0.05$)

Table 7 Stocks of soil organic C and harvest residue C as well as the harvest residue C/N ratio in the upper soil layer (0-30 cm) of three sites directly after re-conversion with three tillage treatments and one year after re-conversion as arable and grassland

	Soil organic C (t/ha)			Harvest residue C (t/ha)			Harvest residue C/N		
	years after conversion			years after conversion			years after conversion		
		Arable	Grassland		Arable	Grassland		Arable	Grassland
	0	1	1	0	1	1	0	1	1
Georgenhof willow									
Shallow tillage	78 a	83 a	84 a	16.5 a	3.4 b	4.9 b	123	69 a*	69 a*
Medium tillage	78 a	83 a	76 a	22.7 a	7.6 ab	7.9 ab	123	68 a*	86 a*§
Deep tillage	84 a	69 a	83 a	18.7 a	11.8 a	9.8 a	123	73 a	93 a
Georgenhof poplar									
Shallow tillage	80 a	65 a*	70 a	23.7 a	6.5 a*	13.8 a	80	76 a	100 a*
Medium tillage	76 a	75 a	70 a	22.7 a	11.7 a	8.8 a	80	79 a	94 a*
Deep tillage	83 a	76 a	74 a	30.5 a	11.3 a	15.0 a	80	99 a	97 a
Wachtum poplar									
Shallow tillage	108 a	101 a	102 a	32.5 a	8.8 a	16.0 a	66	40 a*	67 a§
Medium tillage	112 a	118 a	96 a	30.8 a	4.8 a	6.7 a	66	39 a*	53 a*§
Deep tillage	114 a	125 a	110 a	39.0 a	16.9 a	14.7 a	66	49 a	66 a
CV (± %)	17	27	19	48	42	48	1	15	11

CV = mean coefficient of variation between replicate samples (n = 3); different letters indicate a significant difference between tillage treatments; * significant difference between years; § significant difference between arable and grassland use ($P < 0.05$)

5.3.4 Distribution of C in aggregate and density fractions

Recovery of soil after aggregate fractionation varied between 96 and 104%, whereas the proportion of C to SOC was normalized to a 100% recovery. Results of the aggregate fractionation are pooled for the three tillage treatments in the particular land use types, as no differences among tillage treatments were observed at either of the sampling dates. Macroaggregates (250–2000 μm) comprised on average 90% of SOC after re-conversion at both Georgenhof sites and declined by 7% under arable use, accompanied by a corresponding increase in microaggregate (53-250 μm) associated C (Fig. 7 a/b).

At Georgenhof poplar, more macroaggregate C and less microaggregate C contributed to SOC under grassland than under arable use one year after re-conversion. At Wachtum, macroaggregates contained 69% SOC and decreased under arable use as well as under grassland use by 9 and 11%, respectively, accompanied by an equivalent increase in the microaggregates one year after re-conversion (Fig. 7c). The proportion of C declined in the fraction < 53 μm within one year under arable use at Wachtum. As the C content of the particular fractions remained constant, the changes were caused only by the fraction mass (data not shown).

Directly after re-conversion, the free light fraction comprised 10 and 8% and the occluded light fraction 21 and 16% of SOC, averaged over all three tillage treatments at Georgenhof willow and poplar, respectively (Table 9). Free LF-C tended to decrease and occluded LF-C to increase at both Georgenhof sites with few exceptions. At shallow and medium tilled Georgenhof poplar, 9% less SOC was associated with occluded light fraction under arable than under grassland use. At both sites and both land use types, most occluded LF-C occurred in the deep tillage treatments. In the sandy soil Wachtum, LF-C contributed between 85 and 91% to SOC directly after conversion, which decreased significantly after one year only in the medium tilled arable use by 10%.

Table 8 Contents of microbial biomass C, the microbial C/N ratio and microbial biomass C to soil organic C ratio in the upper soil layer (0-30 cm) of three sites directly after re-conversion with three tillage treatments and one year after re-conversion as arable and grassland

	Microbial biomass (C kg/ha)			Microbial biomass C/N			Microbial biomass C/SOC (%)		
	years after conversion			years after conversion			years after conversion		
		Arable	Grassland		Arable	Grassland		Arable	Grassland
	0	1	1	0	1	1	0	1	1
Georgenhof willow									
Shallow tillage	1557 a	1142 a	783 a	5.3 a	7.9 a*	7.2 a	2.0 a	1.4 ab	1.0 a
Medium tillage	1769 a	1373 a	1053 a*§	5.6 a	8.2 a*	7.4 a*§	2.3 a	1.7 a	1.4 a*
Deep tillage	2099 a	758 a	732 a*	5.4 a	7.7 a	7.4 a	2.5 a	1.1 b	0.8 a*
Georgenhof poplar									
Shallow tillage	2261 a	1186 a*	1206 a	7.1 a	8.1 a	7.2 a	2.8 a	1.8 a	1.7 a
Medium tillage	1864 a	1402 a	1448 a	5.5 a	7.7 a	7.4 a*	2.4 a	1.9 a	2.2 a
Deep tillage	2022 a	959 a	1113 a	4.8 a	7.1 a	7.9 a	2.3 a	1.3 a	1.5 a
Wachtum poplar									
Shallow tillage	1495 a	677 a	1045 a§	9.5 a	6.2 a	6.3 a	1.4 a	0.7 a	1.0 ab§
Medium tillage	1015 a	920 a	1398 a	7.7 a	6.0 a	6.9 a	1.0 a	0.8 a	1.5 a§
Deep tillage	1774 a	1046 a	978 a	10.0 a	5.1 a	9.3 a	1.6 a	0.8 a	0.8 b
CV (± %)	31	27	27	19	26	17	28	20	33

CV = mean coefficient of variation between replicate samples (n = 3); different letters indicate a significant difference between tillage treatments; * significant difference between years; § significant difference between arable and grassland use ($P < 0.05$)

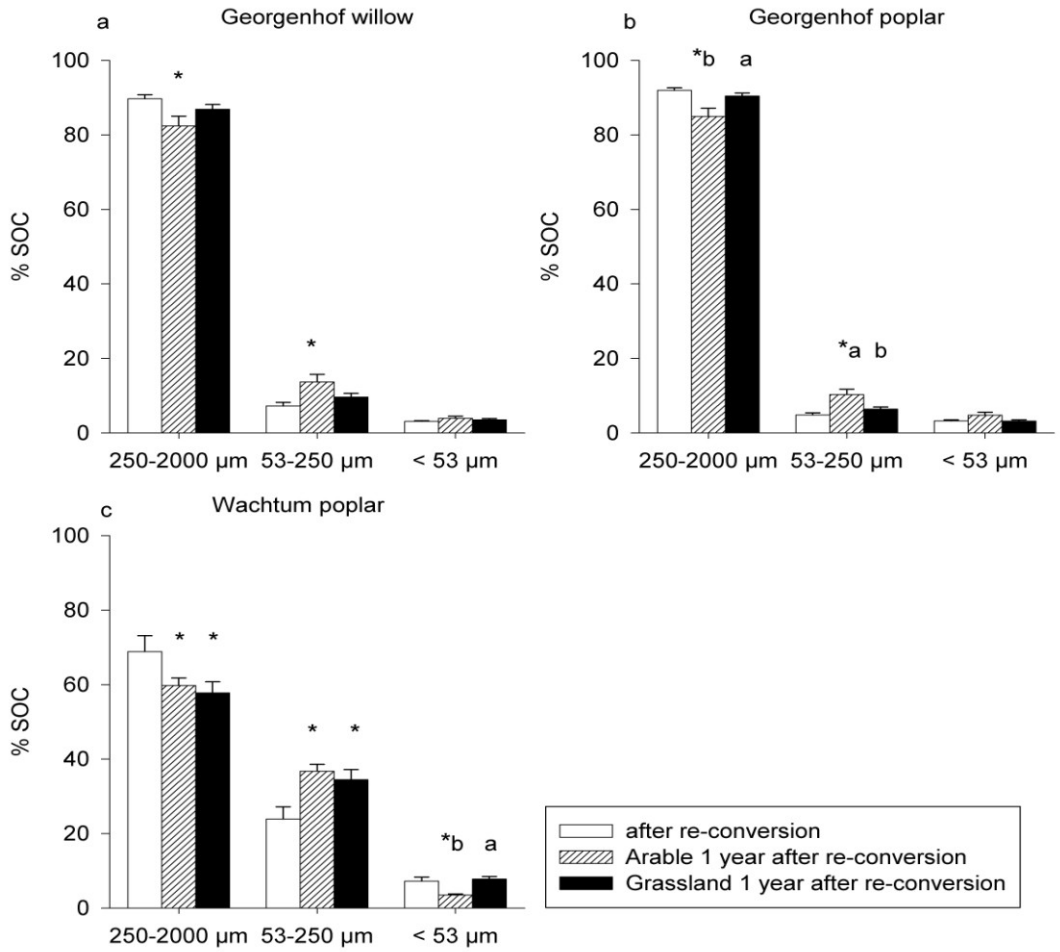

Fig. 7 Contribution of aggregate size fractions in the mineral fine soil to total soil organic C (SOC) in the upper soil layer (0-30 cm) of three sites directly after re-conversion and one year after re-conversion as arable and grassland averaged for the three tillage treatments; error bars show standard error (n = 9), * significant difference between years, different letters indicate a significant difference between arable and grassland ($P < 0.05$)

Table 9 Contribution of light fractions (LF) in the mineral fine soil to total soil organic C (SOC) in the upper soil layer (0-30 cm) of three sites directly after re-conversion with three tillage treatments and one year after re-conversion as arable and grassland

	Free LF (% SOC)			Occluded LF (% SOC)		
	Years after conversion			Years after conversion		
		Arable	Grassland		Arable	Grassland
	0	1	1	0	1	1
Georgenhof willow						
Shallow tillage	13.0 a	9.2 a	6.8 a	19.4 a	26.6 a	23.7 a
Medium tillage	10.3 a	6.9 a	7.0 a	22.3 a	25.1 a	23.0 a
Deep tillage	7.5 a	10.5 a	11.0 a	21.5 a	34.6 a	27.0 a
Georgenhof poplar						
Shallow tillage	8.0 a	4.6 a	2.1 a	12.8 a	11.3 b	20.5 a§
Medium tillage	7.4 a	4.4 a	6.7 a	18.9 a	11.1 b	20.5 a§
Deep tillage	9.0 a	5.1 a	4.5 a	15.6 a	24.7 a	23.4 a
Wachtum poplar						
Shallow tillage	85.1 a	85.9 a	79.8 a			
Medium tillage	89.9 a	79.1 a*	73.9 a			
Deep tillage	91.5 a	79.7 a	86.9 a			
CV (± %)	34	36	35	31	29	18

CV = mean coefficient of variation between replicate samples (n = 3); different letters indicate a significant difference between tillage treatments; * significant difference between years; § significant difference between arable and grassland ($P < 0.05$)

5.4 Discussion

5.4.1 Changes in carbon stocks of the mineral soil and harvest residues

Total C stocks of the mineral fine soil did not change one year after re-conversion of the former tree plantations. This is in accordance with Conant et al. (2007), reporting in a review that no significant changes in soil C stocks were detected within one year after a single tillage event of former no-tilled soils. However, it cannot be excluded that possible short-term changes in SOC induced by tillage depth or land use are smaller than the spatial variability of background SOC levels (Garten and Wullschleger, 1999).

C stored as harvest residues declined distinctly but not significantly one year after re-conversion, due to the high spatial variability of the harvest residues in the field. As C-stocks of the bulk soil did not change, C released by the decomposition of harvest residues may have replenished any possible SOC loss (Sanchez et al., 2007). Distribution of harvest residues in the soil affected the decomposition at Georgenhof willow. The lower loss of harvest residue C in the deep in comparison with the shallow tillage may be caused by less favourable conditions for microorganisms in deeper parts of the soil profile (Olchin et al., 2008). This is suggested by a lower soil microbial biomass content and a higher harvest residue C/N ratio in the deep in comparison with the shallow tillage treatment.

The C/N ratio of the poplar harvest residues directly after re-conversion was lower in comparison with the willow harvest residues. It is probable that the proportion of bark, which has a lower C/N ratio than wood (Tharakan et al., 2003), contributed more to the above- and belowground poplar biomass. Generally, higher bark proportions of willows compared to poplars have been observed (Tharakan et al., 2003), but most studies referred to trees with a shorter rotation length and, as Kenney et al. (1990) reported, the proportion of bark of fast growing willows decreases with increasing age of the stems.

The C/N ratio of the harvest residues may be an indicator of the state of decomposition. Harvest residue C/N at Georgenhof willow and Wachtum was lowered within one year after re-conversion by the C loss due to microbial respiration (Camire et al., 1991; Devine et al., 2006). In contrast, C/N of harvest residues increased at Georgenhof poplar, possibly due to a higher release of labile N components by mineralization or leaching during initial stages of decomposition (Frey et al., 2000). At all sites, the C/N ratio of harvest residues seemed to be higher under grassland, indicating a slower decomposition. Grasslands provide more easily available C and N by root exudates (Bertin et al., 2003), thus reducing the fungal decomposition of recalcitrant material (Vries et al., 2006).

5.4.2 Changes in microbial biomass and microbial ratios

Microbial biomass C decreased one year after re-conversion across all sites, presumably caused by the exhaustion of labile sources of the incorporated harvest residues and easily available C and N sources in the soil (Sanaullah et al., 2011) which became available after the soil tillage during re-conversion. This reduced availability of organic matter is reflected by the low microbial biomass C to SOC ratios (Anderson and Domsch, 1989). Higher microbial biomass C to SOC ratios under grassland in comparison with arable land use types at Wachtum are attributed to the higher content of microbial biomass due to the higher input of easily available C (Bertin et al., 2003).

Hafner and Groffman (2005) reported a decrease in microbial biomass N and an increase in the microbial biomass C/N ratio in forest soils due to a reduction in N availability by woody debris with large C/N ratios. This and a possible shift in the microbial community towards more fungi, which had been shown in a laboratory incubation experiment after the incorporation of poplar harvest residues (Toenshoff et. a. 2012 unpublished), may explain the increased microbial biomass C/N ratios at both Georgenhof sites one year after re-conversion. In contrast, the microbial biomass C/N ratios tended to decrease after one year at Wachtum, but varied widely. Even Joergensen et al. (1995) concluded that in soils with pH below 5, microbial biomass C/N ratios may differ over a wide range.

5.4.3 C distribution in aggregate and density fractions

Previous results (Tönshoff et al., 2012) showed an increased proportion of macroaggregate C to SOC at both Georgenhof sites directly after re-conversion compared to the former tree plantations, despite the intensive soil tillage. The fragmented harvest residues acted as cores for macroaggregate formation (Puget et al., 2000; Six et al., 2000), but the repeated soil tillage of the arable treatments one year after re-conversion reduced macroaggregate C again. This is accompanied by increasing microaggregate C, because macroaggregate occluded microaggregates were released from the disrupted aggregates as well as previously protected organic binding agents, which then became accessible to biodegradation (Balesdent et al., 2000; Six et al., 2000; Chen et al., 2009). In contrast, macroaggregate C remains constant under grassland, due to the better stabilization of macroaggregates (Grandy and Robertson, 2007). This slower aggregate turnover promotes the formation of stable microaggregates within the macroaggregates in which C can be stabilized in the long term (Six et al., 2000).

Moreover, DeGryze et al. (2004) and Helfrich et al. (2008) reported that the transfer of residue-derived C into microaggregates seemed to occur within macroaggregates.

At Wachtum, macroaggregate C decreased under arable use as well as under grassland use because of the weaker stable aggregate formation in this coarse-textured soil. This prevents the physical protection of the residue input (Tisdall and Oades, 1982; Chen et al., 2009), as reflected by the high proportion of LF-C at SOC. However, under arable use, the lower C proportion in the fraction < 53 µm and the higher proportion of C to SOC in the fraction 53-250 µm reveal a formation of new microaggregates within one year after re-conversion by organo-mineral interactions (Lehmann et al., 2007) or by surrounding of fragmented residues by silt and clay particles (Tisdall and Oades, 1982). Tillage depth did not affect C distribution in aggregates one year after re-conversion at any of the sites. However, frequent aggregate disruption by deep tillage under arable use may negatively affect soil aggregate stability compared to reduced tillage thus lowering long-term stabilization of SOC (Six et al., 2000). In contrast Paul et al. (2013) observed that 3-year conventional tillage combined with residue retention increased soil C content at 15–30 cm depth in comparison to reduced tillage thus resulting in no different C contents when considering the upper 30 cm of the soil.

Rapid initial C-losses after soil tillage are mainly due to mineralization of labile pools such as light fraction organic matter (Okore et al., 2007) and may be an early indicator for changes of total SOC (Haynes, 2005). For instance, Motavalli et al. (2000) reported 35% less LF-C one year after conversion of forest ecosystems into arable use and Okore et al. (2007) observed 40% less LF-C in a sandy loam 5 years after conversion. This is in accordance with the decrease in free light fraction organic matter at the Georgenhof sites and LF-C at Wachtum, respectively.

However, a loss in one SOC fraction may be offset by gains in other fractions, leading to no apparent change in total SOC (Schwendemann and Pendall, 2006). Increased amounts of occluded LF-C one year after re-conversion at the Georgenhof sites indicate that formerly free light fraction may have been occluded and stabilized into aggregates (Six et al., 2000). This is especially true for grassland sites (Chan, 2001), explaining the higher proportion of occluded LF-C in grassland in comparison with arable use at Georgenhof poplar one year after re-conversion.

The higher proportion of occluded LF-C at SOC in all deep tillage treatments in comparison with the less intensive tillage systems supports the assumption of Balesdent et al. (2000) and Olchin et al. (2008) that the tillage intensity affects the occlusion of LF-C into

aggregates, as light fraction organic matter is exposed to a greater soil volume. Therefore, deep tillage during re-conversion followed by reduced or no further frequent tillage may potentially serve as a strategy to reduce or sequester soil C.

5.5 Conclusions

Re-conversion of tree-plantations to arable use did not result in a loss of bulk SOC after one year. However, the decreases in free light organic matter fractions, macroaggregate associated C and microbial biomass C indicate a loss of SOC. High losses of harvest residue C, accompanied by decreased C/N ratios have been observed, but due to high spatial variability, effects of tillage depths and land-use were usually not significant. Nevertheless, a decrease in the microbial biomass C to SOC ratio suggests a retarded residue decomposition, especially in the deep tillage treatment. Grassland use as subsequent land-use provides a higher proportion of SOC associated with macroaggregates and as occluded LF-C, protecting organic matter physically against microbial decomposition at the loamy Georgenhof sites. Contrary to our hypothesis, these results imply that deep tillage during re-conversion can potentially mitigate C-losses when combined with the absence of further tillage. Further research in the coming years is necessary to assess the effects of the different tillage depths, in particular in the frequently tilled arable treatments, on C dynamics in soil and harvest residues, in order to recommend an appropriate re-conversion strategy. As a recommendation for other studies, spatial heterogeneity can be decreased if total aboveground harvest residues had been removed after the final harvest and a defined mass of residues had been be re-applied to a subplot of the site before re-conversion. Furthermore by comparing the control with the harvest residue treated plots, C-dynamics of only belowground and both belowground as well as both, aboveground and belowground could be observed.

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6. Initial decomposition of post-harvest crown and root residues of poplars as affected by N availability and particle size

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Abstract

An incubation experiment was carried out to investigate the impacts of residue particle size and N application on the decomposition of post-harvest residues of fast growing poplar tree plantations as well as on the microbial biomass. Crown and root residues, differing in their C/N ratios (crown 285, root 94), were ground to two particle sizes and incubated with and without application of inorganic nitrogen (N) for 42 days in a tilled soil layer from a poplar plantation after one year of re-conversion to arable land. Carbon and N mineralization of the residues, microbial biomass C and N, ergosterol contents and recovery of unused substrate as particulate organic matter (POM) were determined. Carbon mineralization of the residues accounted for 26 to 29 % of added C and caused a strong N immobilization, which further increased after N addition. N immobilization in the control soil showed that even one year after reconversion, fine harvest residues still remaining in the soil were a sink for mineral N. Irrespective of the particle size, C mineralization increased only for crown residues after application of N. Nevertheless, the overall decrease in amounts of POM-C and a concurrent decrease of the CN ratio in the POM demonstrate the mineralization of easily available components of woody residues. Microbial biomass significantly decreased during incubation, but higher cumulative CO_2 respiration after N application suggests an increased microbial turnover. Higher ergosterol to microbial biomass C ratios after residue incorporation points to a higher contribution of saprotrophic fungi in the microbial community, but fungal biomass was lower after N addition.

6.1 Introduction

During the re-conversion of fast-growing tree plantations back to arable use, large amounts of fragmented post-harvest residues such as root and crown wood are incorporated into soil (Toenshoff et al. 2012). The re-conversion of the sites involves intensive soil tillage, resulting in a strong mineralization of soil organic matter as well as of the harvest residues. However, little is known about the factors regulating especially the initial C and N mineralization of woody residues (Wal et al. 2007) and the impact on microbial community composition as well as the contribution of bacteria and fungi to residue decomposition.

Decomposition of plant residues is controlled by factors such as their C/N ratio, N concentration, biochemical characteristics and particle size (Angers and Recous 1997; Tarafdar et al. 2001; Wang et al. 2004; Abiven et al. 2005). It is assumed that the mineralization is higher, the more N is provided by the residues and the lower the contents of recalcitrant components such as lignin (Camire et al. 1991). Commonly, the initial decomposition of woody residues is limited by their low N concentrations (Recous et al. 1995; Mary et al. 1996; Henriksen and Breland 1999). This enhances the N immobilization in soils by microorganisms (Recous et al. 1995; Hafner and Groffman 2005; Muhammad et al. 2011) and reduces the N availability for the subsequent crops. Thus, after re-conversion of tree plantations, N fertilization appears to be necessary to prevent reduced yields. Nitrogen addition often results in a higher mineralization of residues, since it releases the N limitation for microorganisms (Recous et al. 1995). However, it has also been reported to retard the decomposition of lignified plant tissue (Camire et al. 1991; Carreiro et al. 2000; Wang et al. 2004), particularly due to a reduction of the saprotrophic fungal biomass (Henriksen and Breland 1999; de Vries et al. 2006). The surface of residues exposed to decomposition varies according to the particle size (Tarafdar et al. 2001). With decreasing particle size the surface area to volume ratio increases and causes a better contact between residue particles and soil, thus enhancing the microbial decomposition (Ambus and Jensen 1997; Henriksen and Breland 2002). For investigating decomposition processes of different sized residues, an optimum contact between residues and the mineral soil should be provided by homogeneously mixing the residues with the soil (Angers and Recous 1997). To assess the effects of different particle size on residue decomposition, determination of the recovery of the remaining components of the incorporated residues after a defined decomposition time by analyzing the particulate organic matter (POM) is an important tool (Muhammad et al. 2006).

The heterogeneous incorporation of harvest residues in the soil after the re-conversion of tree-plantations and the different fragment sizes lead to high spatial variability of soil C

fractions (Toenshoff et al. 2012), which makes the interpretation of management effects on soil C- and N-dynamics difficult. In the present study a laboratory incubation experiment with ground harvest residues was carried out to overcome this spatial variability and to provide a homogeneous incorporation of the residues to soil. Crown and root residues, differing in their C/N ratio (crown 285, root 94), were ground to two particle sizes and incubated with and without N addition. Our objectives were (1) to assess whether crown and root residues decompose differently, (2) to investigate the response of crown and root residue mineralization to increasing N availability and decreasing particle size, (3) to study how residue mineralization affects the dynamics of the inorganic N pool and (4) to elucidate how the incorporation of the residues and increasing N availability affect the microbial activity, considering particularly the assumption that the incorporation woody residues promotes saprotrophic fungi in the soil microflora.

6.2 Material and Methods

6.2.1 Soil and plant residues

The soil was sampled in October 2011 at 0-30 cm from a former poplar fast growing tree plantation at the site Georgenhof (51°27'N, 9°0'O, 320 m a.s.l.), which had been converted back to arable use one year before sampling. The soil is a silty loamy Stagno-Gleyic Cambisol (FAO-WRB 2006) with 19% sand, 64% silt, 17% clay, a pH of 5.6, an organic C content of 19 mg g^{-1} soil and a C/N ratio of 12. Crown and root material of the poplars was collected before final harvest of the trees and dried at 60°C. Roots were excavated on a 1.4 × 1.4 m square, centred around five selected trees until a depth of 30 cm and were separated into coarse (> 5 mm) and fine (< 5 mm) roots. As the C/N ratio between coarse and fine roots differed only slightly (Toenshoff et al. 2012), coarse and fine roots were mixed in a ratio of 70/30 as previously determined in the field and contained 47% C and 0.50% N (C/N = 94). The crown contained 48% C and 0.17% N (C/N = 285). Each residue was ground to 1-5 mm (coarse) or to < 1 mm (fine) with a mill.

6.2.2 Incubation experiment

The kinetics of the C and N mineralization of the crown and root residues were studied in an incubation experiment and the effect of two different residue sizes (coarse = 1-5 mm and fine = < 1 mm) and two different levels of nitrogen (no N addition = -N and N addition = +N) on

decomposition and microbial biomass were examined. Soil samples without residue amendment or a N addition alone were included as control treatments, thus resulting in a total number of 10 treatments: (1) control, (2) control +N, (3) crown coarse -N, (4) crown fine -N, (5) root coarse -N, (6) root fine -N, (7) crown coarse +N, (8) crown fine +N, (9) root coarse +N and (10) root fine +N.

The moist soil was sieved to 2 mm and pre-incubated at 20°C for 7 days before incubation. For measuring C mineralization of each of the treatments, moist soil equivalent to 200 g dry soil adjusted to 50% water holding capacity, were weighed into 1.5 l glass jars in four replicates per treatment and incubated for 42 days at 20°C in the dark. Crown or root residues of each particle size were added and thoroughly mixed with the soil just before incubation at a rate of 6.1 mg C g^{-1} dry soil and 20 µg N g^{-1} dry soil for the crown and 65 µg N g^{-1} dry soil for the roots. The amount of C added with the residues was calculated according the amount of C of roughly 19 t ha^{-1}, which was incorporated to soil with the harvest residues in the field during re-conversion of the poplar plantation. Inorganic N was added to the soil at incubation start as NH_4NO_3 solution according to 20 µg N g^{-1} dry soil or 30 kg N ha^{-1}, corresponding to the N fertilization conducted in the field. For measuring C mineralization, a CO_2 trap (10 ml 0.5 M NaOH) was placed in each jar. Additionally, a trap was placed in four empty jars as blanks. The CO_2 traps were replaced after 1, 3, 7, 10, 14, 21, 28, 35 and 42 days and the CO_2 evolved was determined by back-titration with 0.5 M HCl after adding 5 ml of a saturated $BaCl_2$ solution to precipitate the Na_2CO_3. Carbon mineralization was calculated as the difference between the samples with residues and the corresponding control samples.

6.2.3 Soil analysis

Microbial biomass C and N, inorganic N, the fungal cell-membrane component ergosterol and particulate organic matter (POM) for each of the 10 treatments was determined on soil samples equivalent to 200 g dry soil adjusted to 50% water holding capacity and placed in 0.5 l polyethylene flasks in four replicates per treatment and sampling date and incubated for 42 days at 20°C in the dark. At day 0, 14, 28 and 42 four replicates of each variant were destructively sampled for determination of microbial biomass C and N and inorganic N, whereas ergosterol and POM were measured only at day 0 and 42. For estimating microbial biomass C (Vance et al. 1987), two portions of 15 g moist soil were extracted with and without $CHCl_3$ fumigation with 60 ml 0.5 M K_2SO_4. Organic C and total N in the extracts were measured after combustion using a multi N/C Analyser (Analytik Jena, Jena, Germany). Microbial biomass C and N were calculated as the difference between fumigated and non-

fumigated samples using a k_{EC} value of 0.45 (Wu et al. 1990) and a k_{EN} value of 0.54 (Brookes et al. 1985) to account for the non-extractable part. Non-fumigated K_2SO_4 soil extracts were analysed for NH_4^+–N and NO_3^-–N by colorimetric analysis with a continuous flow analyser (Evolution2, Alliance, Friedrichsdorf, Germany) at 540 nm. Cumulative net N mineralization from the residues was calculated as the difference between the net mineralization in the controls and the amended soils by subtracting sum of the inorganic N forms at the end of the incubation time of the initial inorganic N in soil.

Ergosterol was extracted and measured according to Djajakirana et al. (1996). 2 g moist soil was extracted with 100 ml ethanol by 30 min oscillating shaking at 250 rev min^{-1}. Ergosterol was determined by reversed-phase HPLC with 100% methanol as the mobile phase and detected at a wavelength of 282 nm.

POM was determined after the method by Magid and Kjærgaard (2001). 100 g soil was dispersed in 1000 ml 5% NaCl, shaken by hand and allowed to stand over night. Then the samples were poured gradually onto sieves of 400 µm and 63 µm mesh sizes and washed with tap water. The aggregates were destroyed by pushing the soil through the sieve during the washing procedure until the water passing through the sieve became clear. The material retained on the sieves was transferred into a beaker. Tap water was added, the beaker was swirled and organic material was separated from the mineral material by flotation-decantation. Swirling and flotation-decantation was repeated until organic particles were no longer visible in the mineral fraction, which was discarded. The remaining POM fractions were combined, dried at 60°C for 48 h, weighed and ground for total C and N analysis. Values for POM from the control soils have been subtracted from the treatments to describe the recovery of unused crown and root residues as POM.

6.2.4 Statistical analysis

The results presented in the tables are arithmetic means and expressed on an oven-dry basis (about 24 h at 105°C). In the treatments, significant experimental effects were tested by three-way ANOVA using organic amendment, particle size and N addition as independent factors. Changes in ergosterol and POM between day 0 and day 42 were calculated with a paired t-test ($P < 0.05$). All statistical calculations were performed using JMP 9.0 (SAS Institute Inc.).

6.3 Results

6.3.1 C mineralization and POM recovery

The cumulative CO_2-C respiration of the treatments was higher than for the respective control soil, whereas N addition slightly increased respiration in the treatments amended with crown residues (Table 10).

Table 10 Cumulative respiration in control soils and amended soils as well as net cumulative C and N mineralization (difference method) in soils amended with crown and roots residues of two particle sizes without and with N addition over the 42 d incubation; probability values of three-factorial ANOVA for amendment treatments

	cumulative respiration	cumulative C mineralization	cumulative N mineralization
	mg CO_2-C kg soil^{-1}	% added C	mg N kg^{-1}
Control soils			
- N	0.4		- 38
+ N	0.4		- 188
Organic amendment			
Crown	2.3	29	- 142
Root	2.1	27	- 109
Particle size			
coarse	2.2	28	- 117
fine	2.2	28	- 134
N addition			
- N	2.1	26	- 95
+ N	2.3	29	- 157
Probability values			
Organic amendment (OA)	<0.01	<0.01	<0.01
Particle size (PS)	ns	ns	0.02
N-fertilization (N)	<0.01	<0.01	<0.01
OA x N	<0.01	<0.01	<0.01
CV (± %)	2.8	2.5	15

CV = mean coefficient of variation between replicate incubations (n = 4); ns = not significant; interactions OA x PS and PS x N are not significant

Carbon mineralization of the residues rapidly increased in all treatments after incubation start and up to 16% of the C initially present in the residues was lost as CO_2 until day 14 (Fig. 8). Thereafter mineralization rate slowed down until the end of incubation. Cumulative C mineralization of the root residues accounted on average 27% of added C at day 42 (Table 10, Fig. 8a). But it cannot be excluded that the addition of the residues caused a priming effect, resulting in an overestimation of the amount of residue C mineralized due to the mineralization of organic carbon of the mineral soil. Carbon mineralization dynamics of the crown treatments differed not until day 14 but thereafter N addition promoted crown mineralization of both particle size classes, resulting in a significantly higher cumulative C mineralization of 29% in comparison with 26% without N addition (Table 10, Fig. 8b). C mineralization of roots did not differ irrespective of N addition.

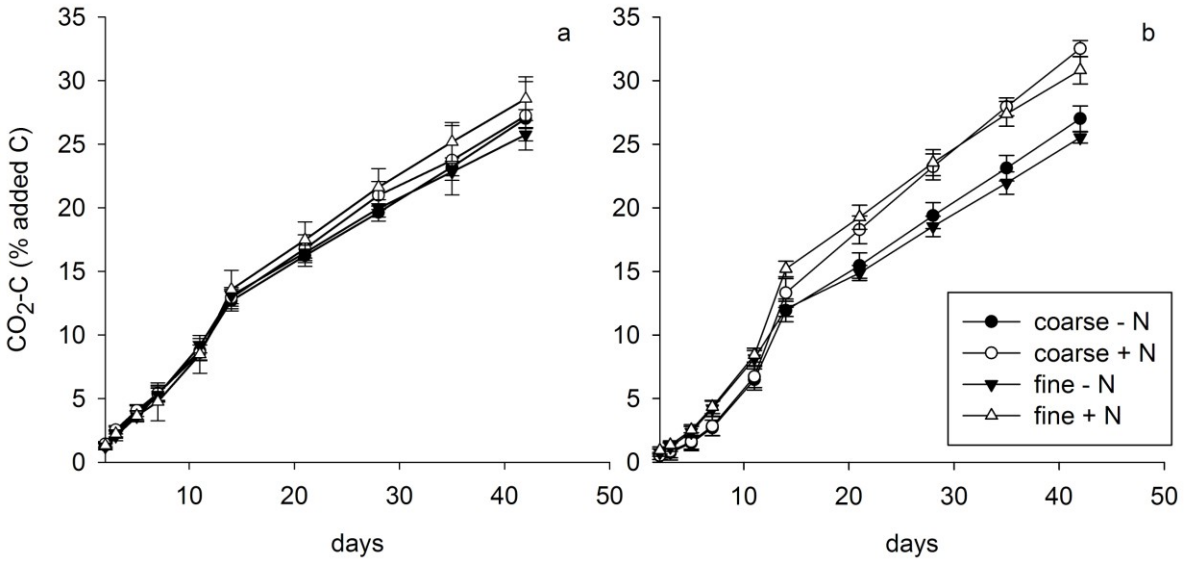

Fig. 8 Net cumulative CO_2 mineralization (expressed as % added C) of (a) roots and (b) crown residues of two particle sizes without (filled symbols) and with N addition (opensymbols) during the 42-day incubation; error bars show standard error (n = 4)

At day 0, recovery of the added residues as POM accounted on average 55 ±15 % for the coarse sized and only 25 ±6 % for the fine sized residues. Only changes in recovered POM-C between the two sampling dates and not related to the total added residue C was calculated due to this incomplete recovery. In all treatments, POM-C and C/N ratio decreased significantly throughout incubation during the progressive decomposition process (Table 11). No increase in the total amounts of N was detected in the POM in none of the treatments (data

not shown). POM-C at the start of incubation was higher for the crown than for the root residues, but no longer differed after 42 days of incubation. Although no difference was observed in C recovered as POM after 42 days of incubation between coarse and fine particle size, regardless of N addition, POM derived from fine particles had a significantly lower C/N ratio.

Table 11 Amounts of C and C/N ratio of particulate organic matter in control soils and soils amended with crown and roots residues of two particle sizes without and with N addition at the beginning and the end of the 42-day incubation and % recovered C from day 0; probability values of three-factorial ANOVA for amendment treatments

	POM-C > 63µm			POM > 63µm	
	µg g^{-1} soil		% recovered C	C/N	
	Day		from day 0	Day	
	0	42		0	42
Control soils					
Control –N	0.8	0.7	88	28	26
Control +N	0.8	0.7	88	28	26
Organic amendment					
Crown	3.5	1.9*	57	125	77*
Root	2.6	2.1*	80	77	66*
Particle size					
coarse	4.2	2.8*	73	106	81*
fine	1.9	1.2*	64	96	62*
N addition					
- N	3.0	1.9*	66	100	72*
+ N	3.0	2.1*	70	101	71*
Probability values					
Organic amendment (OA)	<0.01	ns	0.02	ns	<0.01
Particle size (PS)	<0.01	< 0.01	ns	<0.01	<0.01
N-fertilization (N)	ns	ns	ns	ns	ns
OA x PS	0.04	ns	ns	0.02	ns
CV (± %)	13	18	25	9	12

CV = mean coefficient of variation between replicate incubations (n = 4); * significant difference between days (P < 0.05); interactions OA x N and PS x N are not significant

6.3.2 N mineralization

Incorporation of crown and root residues resulted in net immobilization of inorganic N in all treatments and was greater following incorporation of fine than coarse residues (Table 10). N immobilization in all treatments was highest during the period of highest residue decomposition with 134 mg N kg^{-1} soil immobilized for the -N treatments and between 170 and 323 mg N kg $soil^{-1}$ for the +N treatments within the first 14 days (Fig. 9). In the residue amended treatments without N addition, inorganic N was then nearly depleted until end of incubation with values fluctuating around 10 mg N kg^{-1} soil. N addition increased net N immobilization by the crown residues while N immobilization by the root decomposition was not higher than in the control soil (Table 10 and Fig 9b). The content of inorganic N in the -N control treatment remained relatively constant during incubation (Fig. 9a). In contrast, in the control +N treatment inorganic N strongly decreased during the first 14 days and reached then the level of the control -N treatment until the end of incubation (Fig. 9b).

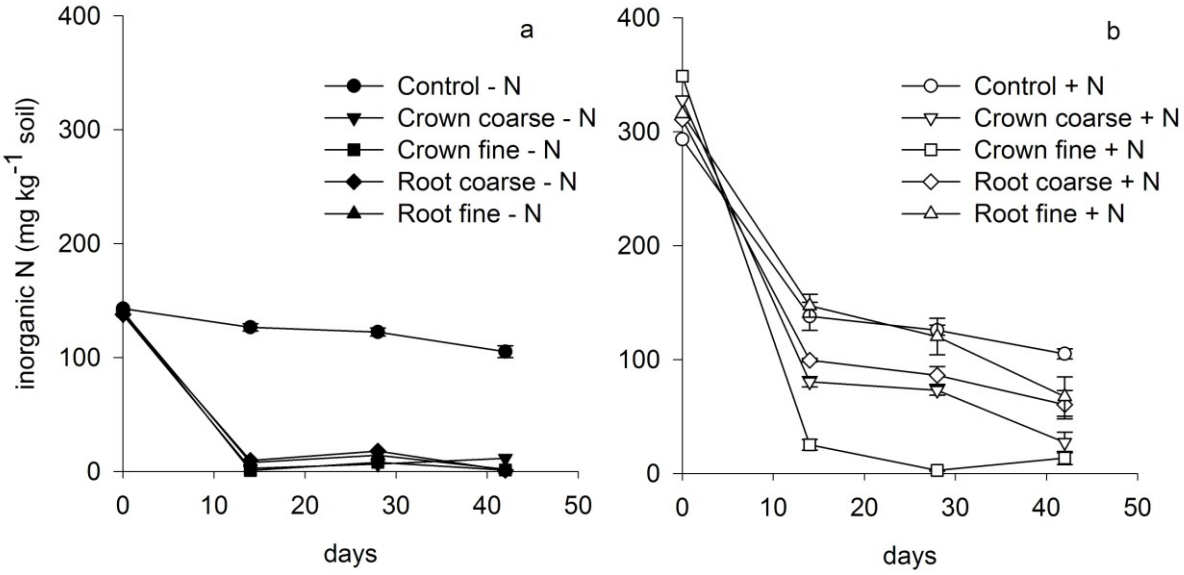

Fig. 9 Evolution of inorganic N in control soils and in soils amended with crown and root residues of two particle sizes (a) without (filled symbols) and (b) with N addition (opensymbols) during 42-day incubation; error bars show standard error (n = 4)

6.3.3 Microbial biomass and ergosterol

Microbial biomass C decreased gradually during incubation in all treatments and was significantly lower at the end of incubation than at the beginning (Fig. 10a/b). Microbial biomass N declined during the first 14 days of incubation across all treatments and remained more or less constant in all residue added treatments without N addition as well as in the coarse and fine root +N treatments until end of incubation (Fig. 10 c/d).

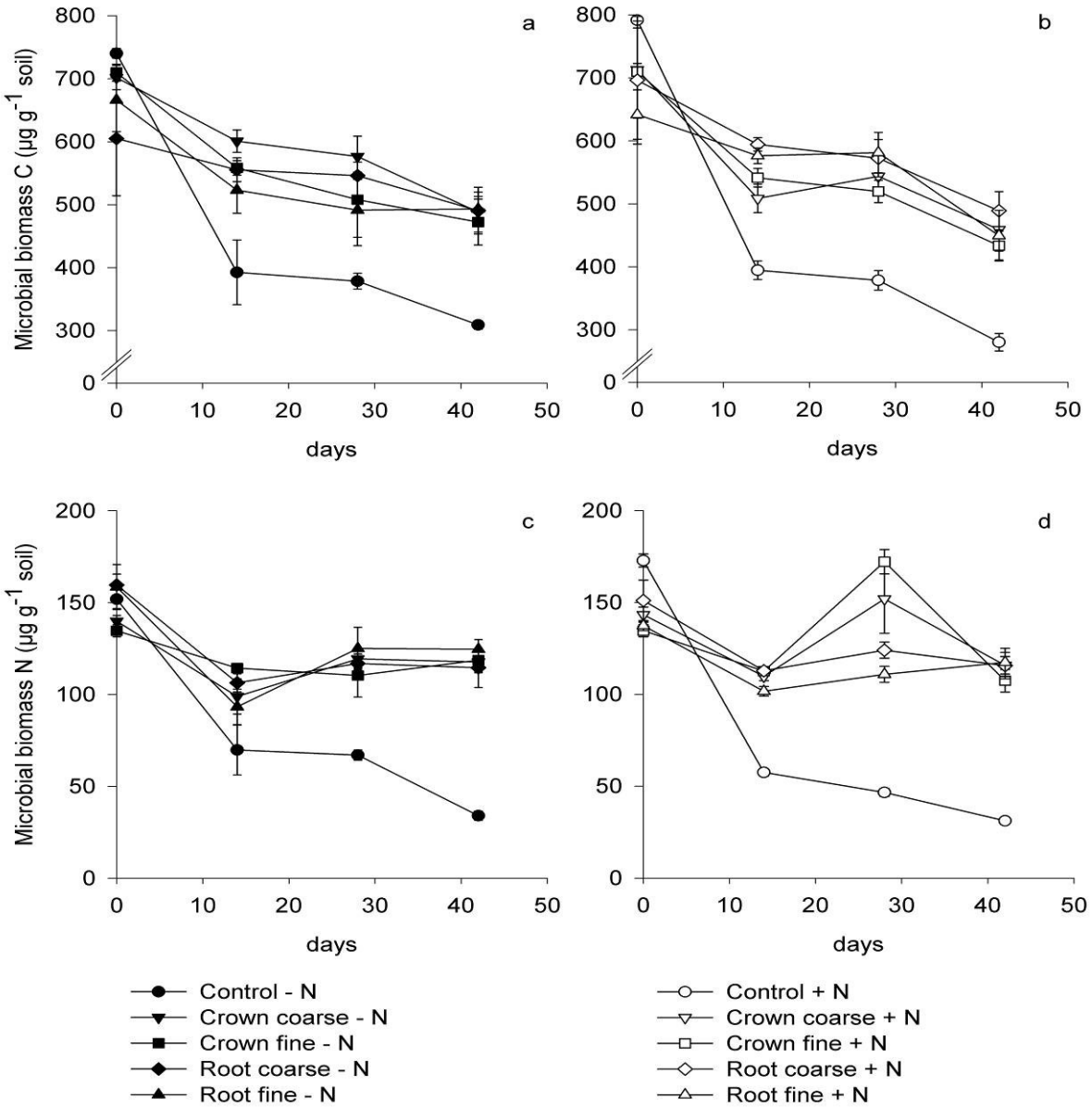

Fig. 10 Changes in (a/b) microbial biomass C and (c/d) microbial biomass N in control soils and in soils amended with crown and root residues of two particle sizes without (filled symbols) and with N addition (opensymbols) during 42-day incubation; error bars show standard error (n = 4)

In the crown +N treatments of both particle sizes, an increase in microbial biomass N was observed between day 14 and 28. ANOVA for day 28 (data not shown) revealed an organic amendment × N addition interaction ($P < 0.01$) with higher microbial biomass N for the crown +N than for the root +N treatments. Neither microbial biomass C nor microbial biomass N was affected by organic amendment, particle size or N addition at any other sampling date. At incubation start microbial biomass C and N contents of the control soils differed not from those of the treatments but were significant lower at all other sampling dates. At the start of incubation, microbial biomass C and N contents of the control soils did not differ from those of the treatments, but were significantly lower at all other sampling dates.

Table 12 Ergosterol content and ergosterol to microbial biomass C ratio in control soils and in soils amended with crown and root residues of two particle sizes without and with N addition at the beginning and the end of the 42-day incubation (n = 4); probability values of three-factorial ANOVA for amendment treatments

	Ergosterol µg g soil^{-1}		Ergosterol/microbial biomass C %	
	day 0	42	day 0	42
Control soils				
Control	0.6	0.5*	0.01	0.18*
Control + N	0.7	0.7	0.01	0.25*
Organic amendment				
Crown	1.2	1.7*	0.16	0.35*
Root	1.3	1.6	0.22	0.34*
Particle size				
coarse	1.3	1.7*	0.20	0.35*
fine	1.2	1.5*	0.18	0.34*
N addition				
- N	1.2	1.7*	0.20	0.36*
+ N	1.3	1.5	0.18	0.33*
Probability values				
Organic amendment	ns	ns	0.03	ns
Particle size	ns	ns	ns	ns
N-fertilization	ns	ns	ns	0.04
CV (± %)	19	24	27	24

CV = mean coefficient of variation between replicate incubations (n = 4); * significant difference between days ($P < 0.05$); all interactions are not significant

The ergosterol content in the residue amended treatments was initially twice as high as in the control soils and increased during incubation, whereas it slightly decreased in the control soils (Table 12). The ergosterol to microbial biomass C ratio varied in a relatively small range and was at incubation start with ratios between 0.16 and 0.22% higher in the treatments than for the control soils. In all treatments and in the control soils, the ergosterol to microbial biomass C ratio increased during incubation. This ratio was higher for the root than for the crown amended soils at incubation start and was affected by N addition at the end of incubation.

6.4 Discussion

6.4.1 Decomposition of crown and root residues

The results clearly demonstrate that decomposition of the crown residues is N limited but N was not limited for the decomposition of roots although both residues having a C/N ratio, exceeding the limit of roughly 25 for N immobilization (Recous et al. 1995; Heal et al. 1997; Hafner and Groffman 2005). Nevertheless, in all treatments residues decompose in two phases: an initial rapid phase in which easily decomposable components of the woody residues are mineralized (Sall et al. 2007; Wal et al. 2007; Xu et al. 2011), followed by a slower decomposition phase in which the retaining, more complex substrates are mineralized (Wang et al. 2004).

The high N immobilization during first stages of decomposition in all residue amended treatments indicates a high N demand during the decomposition of the easily degradable C components (Recous et al. 1995). Nitrogen immobilization is further increased after N addition, suggesting an increased uptake by soil microorganisms if more N is supplied and readily-available C sources are still provided (Zagal and Persson 1994). Even Muhammad et al. 2011 observed that the application of residues and N fertilizer had a lower mineral N pool than soils without N addition due to the immobilization of fertilizer derived N. Hence immobilization of fertilizer N in the field after the incorporation of the residues from short rotation plantations may be high until the easily-decomposable components of the residues are depleted and the N demand of the microorganisms decreases. The N-immobilization rates in the control soils suggest that there is a certain amount of labile carbon present in the soil. Although the soil was sieved < 2 mm, harvest residues which were mixed in the soil during the re-conversion of the study site the year before soil sampling probably have entered the C-pool of the mineral soil and increased the labile C fraction, which was not depleted during preincubation of the soil. Therefore, like in the amended soils, a better N availability

increased N immobilization. On the other hand, most of the residues incorporated into soil under field conditions are coarser than 5 mm, which may not inevitably have negative effects on plant-available N after only the recalcitrant components remain (Quintern et al. 2006). Besides, the N immobilized in the microbial biomass and their residues will be mineralized and become available at a later time. Without N addition, cumulative C mineralization did not differ between crown and root residues, although more N was provided by the roots. Thus, the availability of C and N is not necessarily related to the C/N ratio or the initial organic N concentration of the residues but much more to other biochemical properties of the residues (Camire et al. 1991; Recous et al. 1995; Mary et al. 1996). A lower mineralizing capacity of roots is reported in several studies (Camire et al. 1991; Abiven et al. 2005; Rasse et al. 2005; Sall et al. 2007) and is attributed to a reduced accessibility to decomposers because of the presence of large quantities of suberized cell walls (Abiven et al. 2005; Rasse et al. 2005). This explains why N addition increased C mineralization only for the crown residues (Recous et al. 1995). Moreover, the lower decomposition of the roots explains the lower N immobilization in the root amended treatments. The lack of an N response during the first 14 days of decomposition of the crown residues may be attributed to the initial presence of soil inorganic N (Henriksen and Breland 1999) or to the low C/N ratio of soluble crown components (Bremer et al. 1991).

It is assumed that C mineralization of residues with a high C/N increased with decreasing particle size, which is caused by the improved contact between residues and soil (Jensen 1994; Ambus and Jensen 1997; Tarafdar et al. 2001). For example, Angers and Recous (1997) observed a higher mineralization of < 1 mm sized straw residues compared to > 5 mm sized particles. No difference in C mineralization between the two particle sizes of 1-5 mm and < 1mm occurred in the current study as differences between the particle sizes are small. But possibly, the increased surface of the fine ground residues did not improve the contact between residues and soil particles, as the soil was not compacted during the filling of the incubation jars. Garnier et al. (2008) reported that residue decomposition is lower when soil density is decreased, as this decreases the actual area of contact between residue and soil particles. Furthermore, Bremer et al. (1991) hypothesized that a low N availability in N-depleted residues is responsible for the fact that mineralization did not increase with decreasing particle size.

The overall decrease in POM-C in all treatments throughout the experiment indicates a substantial decomposition of the added residues, although there was no close relationship between changes in POM-C or the amount of POM-C at day 42 and the CO_2 respired.

Nevertheless, higher losses of POM-C in the crown treatments reflect the better degradability of the crown residues. Particle size had no influence on C mineralization and POM, but CN ratio of POM in fine residue treatments was significant lower at the end of incubation. Although a stronger fragmentation of the finer sized residues during the POM extraction at incubation end caused a lower recovery, the higher decrease of the CN ratio indicates a higher residue mineralization. Higher recovery of C amounts in the native POM of both control soils compared to the POM in the treatments reveals the importance of POM as a source of potentially available nutrients after addition of plant residues (Ha et al. 2008). In the control soils, stable C amounts in POM suggest a low nutrient release from native POM compared to POM after residue addition, which was also shown by Ha et al. (2008).

6.4.2 Microbial and fungal biomass dynamics

Microbial biomass C and N decreased during the incubation, as N appears to be limiting to the microbial populations, which is in accordance with results reported by Hafner and Groffman (2005) and Camire et al. (1991) during wood and root decomposition. The distinct decrease of microbial biomass in the control soils is attributed to 7 to 12 t C ha^{-1} of woody residues, still remaining one year after recultivation (Toenshoff et al. unpublished), which probably liberated easily decomposable organic matter beyond the preincubation period but which were then depleted after fourteen days of incubation. Nevertheless, the higher microbial biomass contents in the residue amended treatments compared to the control soils indicate that the recently added plant residues provide more available energy sources than the POM of the control soils as discussed above. Higher CO_2 evolution rates but no increased microbial biomass C in the crown +N compared to the crown –N treatment point to a lower C use efficiency due to a decreased percentage of fungi in the soil microflora after N addition. Although high amounts of soil inorganic N are immobilized during the first 14 days, decreasing microbial biomass N contents suggest that a large fraction of immobilized N is transferred into non-biomass microbial residues such as exo-enzymes, exsudates and the necromass (Bending and Turner 1999; Engelking et al. 2007). This explains the progressive immobilization of soil mineral N during incubation, even though microbial biomass declined (Bending and Turner 1999), while no incorporation of N into the POM was detected (data not shown).

The higher ergosterol contents and the distinctly higher ergosterol to microbial biomass C ratio in the residue amended compared to the control soils at the start of incubation are attributed to a high proportion of wood colonizing fungi. Potthoff et al. (2005) also attributed

a strong influence of residue colonising organisms to the microbial soil community after incorporation of maize residues. As ergosterol is an important indicator for the presence of saprotrophic fungi (Klamer and Bååth 2004; Joergensen and Wichern 2008), the increase in ergosterol but especially in the ergosterol to microbial biomass C ratio shows that the addition of the woody residues with wide C/N ratios promotes the growth of soil fungi (Six et al. 2006). In contrast to the studies of Wal et al. (2007) and Quintern et al. (2006), who observed that N addition positively influenced fungal biomass during initial decomposition of woody residues, the lower ergosterol in the +N compared to the -N treatments may indicate that N addition inhibits lignin degrading saprotrophic fungi or promotes a fungal community containing lower ergosterol concentrations in their biomass. Another explanation is a higher turnover of fungal biomass C, as indicated by the lower ergosterol to microbial biomass C ratio and higher cumulative CO_2 respiration in the +N treatments, reducing the amount of ergosterol accumulated temporarily in dead fungal tissue (Zhao et al. 2005).

6.5 Conclusions

The results of the incubation study confirm the expected high N immobilization potential and promotion of saprotrophic fungi in the microbial community directly after the incorporation of post-harvest poplar crown and root residues. The N immobilization in the control soils revealed that fine sized harvest residues have the potential to immobilize N even one year after their incorporation to soil. N application increases the short term C mineralization of only the crown residues, due to a higher biochemical recalcitrance of root tissues. Residue mineralization was not affected by particle size. Despite high N immobilization rates during decomposition of the residues, the further increasing N immobilization after N addition suggests that N fertilization in the field after the re-conversion of tree-plantations back to arable use may decrease fertilizer use efficiency. However, the lower N immobilization for the coarser sized residues from the plant residues suggests that the incorporation of even coarser residues than 1-5 mm, as observed in the field, may not necessarily reduce N availability for the subsequent crops under field conditions. Moreover, N application seems to increase microbial turnover and to lower the proportion of lignin degrading saprotrophic fungi. Further research on the impact of the initial decomposition stages of woody harvest residues on soil N dynamics at field level is needed to synchronize soil N availability with the plant requirements.

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7. Zusammenfassung

In dieser Arbeit wurde in einem Feldversuch auf drei langjährig als KUP bewirtschafteten Flächen untersucht, wie sich unterschiedliche Bodenbearbeitungstiefen während der Rückführung der KUPs in Acker- und Grünlandnutzung auf die C-Dynamik im Boden auswirken. Im Mittelpunkt stand dabei die Überprüfung der Annahme, ob durch eine reduzierte Bodenbearbeitung und eine nachfolgende Grünlandnutzung die Mineralisierung von organischer Bodensubstanz gemindert werden kann. Vor der letzten Holzernte der KUPs erfolgte die Bestimmung der in der Wurzelbiomasse und der im Boden gespeicherten C-Mengen, um mögliche C-Verluste nach Rückführung der KUPs quantifizieren zu können. Darüber hinaus wurde die Verteilung des C in den Bodenfraktionen der wasserstabilen Aggregate, der leichten organischen Fraktion und der mikrobiellen Biomasse untersucht. Dadurch sollte erreicht werden, auch geringe Änderungen des C-Gehaltes innerhalb kurzer Zeit feststellen zu können. Direkt und ein Jahr nach dem Umbruch wurden durch den Vergleich der C-Gehalte in den Ernteresten sowie in den einzelnen Bodenfraktionen, die Auswirkungen der Rückführung auf die C-Dynamik des Bodens untersucht. Um trotz der Problematik der sehr hohen räumlichen Variabilität der Erntereste im Feld einen tieferen Einblick in die Abbaudynamik von Wurzel- und Kronenmaterial bei unterschiedlicher N-Düngung und Partikelgröße zu bekommen, wurde ein Inkubationsversuch im Labor durchgeführt.

Die Untersuchung vor Umbruch der KUPs zeigte, dass mehr als 90% der unterirdischen organischen Kohlenstoffmenge langjährig bewirtschafteter KUPs im Mineralboden und weniger als 10% in der Wurzelbiomasse gespeichert ist. Dabei nahm die C-Menge in der Wurzelbiomasse in der Reihenfolge Wurzelstock > Grobwurzeln > Feinwurzeln ab. Die langjährige Bodenruhe und der hohe Streueintrag führten zur Herausbildung deutlicher Tiefengradienten der mikrobiellen Biomasse und des organischen Bodenkohlenstoffs, wobei die Fraktion der Makroaggregate den größten Anteil an der organischen Bodensubstanz aufwies.

Nach der letzten Holzernte verblieben hohe Mengen an grob zerkleinerten Kronen- und Stammresten auf den Flächen, die während des Umbruchs der KUPs in den Boden eingearbeitet wurden. Dies führte dem Boden, neben der in der zerkleinerten Wurzelbiomasse gespeicherten C-Menge, große Mengen an zusätzlichem C zu. Der Anstieg des fLF-C direkt nach dem Umbruch der Flächen zeigte, dass auch stark zerkleinerte Erntereste (< 2 mm) in den Boden eingearbeitet wurden. Diese zusätzliche C-Quelle sowie im Zuge der

Bodenbearbeitung verfügbar gewordene, leicht abbaubare organische Verbindungen, steigerten die mikrobielle Aktivität. Durch ihre Ausscheidungsprodukte förderten die Mikroorganismen über die Verkittung von Mikroaggregaten mit den stark zerkleinerten Ernteresten die Aggregatbildung. Dies führte entgegen der Annahme der Zerstörung der Makroaggregate durch die Bodenbearbeitung, zu einer Erhöhung des in der Makroaggregatfraktion gebundenen C und somit zu einer gesteigerten physikalischen Stabilisierung der organischen Substanz gegenüber mikrobiellen Abbau unmittelbar nach dem Fräsen der Flächen.

Ein Jahr nach dem Umbruch führte die erneute Bodenbearbeitung der Ackerparzellen an allen Standorten und in allen Bearbeitungstiefen jedoch zu einer Abnahme des C in der Makroaggregatfraktion, hervorgerufen durch die Zerstörung von Makroaggregaten. Dadurch werden neben Mikroaggregaten auch labile organische Bindungsstoffe freigesetzt, die rasch mineralisiert werden können. Demgegenüber zeigte sich durch die ausbleibende Bodenbearbeitung unter Grünlandnutzung auf beiden Flächen am Georgenhof eine bessere Stabilisierung des C in den Makroaggregaten. Am Standort Wachtum nahm der C in der Makroaggregatfraktion auch unter Grünland nach einem Jahr ab, da die Aggregierung und somit auch die physikalische Stabilisierung der organischen Substanz in dem sandigen Boden gering ist. Dies spiegelte sich in dem hohen Anteil der zusammen extrahierten freien und okkludierten LF wider. Da diese Fraktion nicht an die Mineralmatrix gebunden ist, zeigten sich innerhalb eines Jahres nach dem Umbruch hohe C-Verluste aus dieser Fraktion unter beiden Nachnutzungen.

Auch auf beiden Flächen am Georgenhof zeigten sich hohe C-Verluste in der der fLF, gleichzeitig stieg jedoch der C-Anteil in der oLF, da vormals frei im Boden vorliegende fLF, die hier überwiegend von stark zerkleinerten Ernteresten repräsentiert wird, in Aggregate eingeschlossen und stabilisiert wurde. Der tendenziell höchste Anteil an oLF-C zeigte sich in den tiefen Bearbeitungsvarianten infolge der höheren Okkludierung der fragmentierten Erntereste durch den besseren Kontakt mit den Bodenpartikeln. Entsprechend der höheren Stabilisierung der Makroaggregate unter Grünland, war der Anteil des oLF-C auf der Pappelfläche Georgenhof unter Grünland höher als unter Acker.

Die zunehmende Abreicherung der leicht abbaubaren organischen Verbindungen führte, unabhängig von der Bearbeitungstiefe oder Nachnutzung, auf allen Flächen zu einer Abnahme der mikrobiellen Biomasse ein Jahr nach der Rückführung. Gesunkene C_{mik}/C_{org}-Verhältnisse, als ein Indikator für die mikrobielle Verfügbarkeit und die Qualität organischer Substrate, spiegelten die abnehmende Verfügbarkeit der organischen Substanz wider.

Bereits ein Jahr nach dem Umbruch der KUPs hat die in den Ernteresten gespeicherte C-Menge auf allen Flächen, im Zuge des fortschreitenden mikrobiellen Abbaus, deutlich abgenommen, was sich auf der ehemaligen Weidenfläche sowie in Wachtum in gesunkenen C/N Verhältnissen zeigte. Da sich keine Änderung in der Gesamtkohlenstoffmenge des Mineralbodens feststellen ließ, wurden mögliche Mineralisationsverluste der organischen Bodensubstanz durch Abbauprodukte aus den Ernteresten ausgeglichen. Die oben aufgezeigten Änderungen in den einzelnen C-Fraktionen deuteten ein Jahr nach der Rückführung der KUPs auf erste Verluste an organischen Bodenkohlenstoff aus dem Mineralboden hin. Allerdings erschwerte die sehr heterogene Einarbeitung der Erntereste im Feld die Quantifizierung des Abbaus und ließ keinen Einfluss der Nachnutzung und lediglich am Standort Georgenhof Weide einen Einfluss der Bearbeitungstiefe erkennen. Hier zeigte sich in den tiefen Fräsvarianten eine geringere Abnahme der in den Ernteresten gespeicherten C-Menge gegenüber den flachen Fräsvarianten. Die niedrigen C_{mik} Gehalte und C_{mik}/C_{org} Verhältnisse in den tiefen Fräsvarianten, deuteten auf ungünstigere Verhältnisse für die Mikroorganismen tiefer im Bodenprofil hin. Das höhere C/N Verhältnis der Erntereste unter Grünland gegenüber Ackernutzung auf allen drei Flächen ist auf einen verlangsamten Abbau der Erntereste zurückzuführen, verursacht möglicherweise durch einen geringeren Pilzbesatz infolge höherer, leicht verfügbarer Wurzelausscheidungen unter Grünland.

Im durchgeführten Inkubationsversuch wurde das hohe N-Immobilisierungspotential der Kronen- und Wurzelreste nachgewiesen. Die Mineralisierung leicht verfügbarer organischer Substanzen verursachte insbesondere zu Abbaubeginn der Erntereste eine starke N-Immobilisierung, die nach Zugabe von mineralischen N weiter anstieg. Eine größere Partikelgröße der Erntereste verringerte jedoch das Immobilisierungspotential. Höhere Ergosterol/C_{mik} Verhältnisse nach Zugabe der Erntereste zeigten den gestiegenen Anteil an Lignin abbauenden, saprotrophen Pilzen an der mikrobiellen Gemeinschaft an. Allerdings deuteten niedrigere Ergosterol/C_{mik} Verhältnisse nach der N-Zugabe auf eine Hemmung der saprotrophen Pilze. Aufgrund der hohen Ligningehalte der Wurzeln wurde daher nur die C-Mineralisierung des Kronenmaterials durch die N-Zugabe gesteigert.

Zusammenfassend kann festgehalten werden, dass ein Jahr nach der Rückführung der KUPs in landwirtschaftliche Nutzung die C-Verluste aus den labilen Bodenfraktionen der leichten organischen Fraktion, der mikrobielle Biomasse sowie der Makroaggregate erste Verluste des organischen Kohlenstoffs des Mineralbodens andeuten. Es ließ sich kein Einfluss der unterschiedlichen Frästiefen auf die C-Fraktionen im Mineralboden feststellen, so dass sich im Hinblick auf die anfangs gestellte Annahme einer verringerten C-Mineralisierung durch reduzierte Bodenbearbeitung noch keine Aussage treffen lässt. Die ausbleibende Bodenbearbeitung unter Grünlandnutzung resultierte am Standort Georgenhof jedoch in einer besseren Stabilisierung des C in Makroaggregaten. Eine Quantifizierung des Abbaus der Erntereste in Abhängigkeit der Einarbeitungstiefe oder Nachnutzung wurde durch die sehr heterogene Einarbeitung in den Boden erschwert. Im Inkubationsversuch wurde das hohe N-Immobilisierungspotential der eingearbeiteten Erntereste zu Beginn des Abbaus nachgewiesen, was durch eine zusätzliche mineralische N-Zugabe weiter anstieg. Die Einarbeitung der Erntereste erhöhte in der mikrobiellen Gemeinschaft den Anteil saprotropher Pilze, die bei einer erhöhten N-Verfügbarkeit möglicherweise gehemmt werden. Eine N-Düngung im Feld erscheint daher vor Abbau der leicht verfügbaren organischen Verbindungen der Erntereste nicht sinnvoll.

8. Summary

In the present thesis a field trial at three long-term managed fast growing tree plantations was conducted to investigate the effects of different tillage depths on soil C dynamics during re-conversion of the plantations back to arable and grassland use. It was hypothesized that reduced tillage and a subsequent grassland use will cause a lower mineralization of soil organic matter. Before the final harvest of the trees, C stocks of the root biomass and the bulk soil were determined to quantify possible C losses after re-conversion. The distribution of soil organic carbon in water stable aggregate fractions, light fraction organic matter and microbial biomass was examined to allow detecting even small changes of soil organic carbon. Directly and one year after re-conversion, short term effects on the C dynamics in the soils were studied by comparing the amount of C in the harvest residues and the different C fractions in the mineral soil. But due to the high spatial variability of the harvest residues in the field, interpretation of the decomposition dynamics of the residues was difficult. Therefore a laboratory incubation experiment was carried out to investigate the impacts of residue particle size and N application on the decomposition of crown and root residues.

The results before re-conversion revealed that > 90% of belowground C stocks of long-term managed tree plantations were stored in the mineral soil and < 10% in the root biomass. C stocks of the root biomass decreased in the order root stump > coarse roots > fine roots. The no-tillage management and increased litter amounts caused a distinct depth gradient of microbial biomass and soil organic carbon, whereas most of the SOC was associated with the macroaggregates.

Directly after re-conversion, C stocks of harvest residues increased compared to the C stocks of only the roots. This increase was caused by the incorporation of crown and stem material remaining at the sites after the final harvest. As reflected by the increase in fLF-C after re-conversion, parts of the harvest residues were shredded to particles < 2 mm, providing a C source for the microbial biomass. In contrast to the assumed disruption of macroaggregates during the soil-tillage, the increased production of microbial-derived binding agents induced the formation of macroaggregates by the incorporation and binding of microaggregates with the harvest residues. This resulted in a higher stabilization of organic matter in macroaggregates directly after re-conversion.

One year after re-conversion, the repeated soil tillage of the arable treatments disrupted macroaggregates, reducing the macroaggregate C at all sites. The disruption of the macroaggregates released previously occluded microaggregates as well as organic binding

agents, which then became accessible for biodegradation. In contrast, macroaggregate C was better stabilized under grassland at both Georgenhof sites. At Wachtum macroaggregate C decreased even under grassland use because of the weak stable aggregate formation in this coarse-textured soil, thus preventing the physical stabilization of the residue input. This was reflected by the high proportion of LF-C at SOC, which distinctly decreased within one year. At both sites Georgenhof, fLF-C decreased within one year but increased amounts of oLF-C indicated that formerly free light organic fraction might have been occluded and stabilized into aggregates. The oLF-C tended to be highest in the deep tillage treatments, as the residues were exposed to a larger soil volume. According to the better stabilization of macroaggregates under grassland use, oLF-C was higher under grassland in comparison with arable use at Georgenhof poplar.

Microbial biomass decreased one year after re-conversion across all sites and treatments, caused by the exhaustion of labile sources of the incorporated harvest residues and easily degradable C and N sources of the soil, which became available after tillage. The reduced availability of organic matter was reflected by decreased microbial biomass C to SOC ratios as an indicator for the availability of organic substrates.

One year after re-conversion, harvest residue C declined distinctly by the progressing microbial decomposition, accompanied by decreasing residue C/N ratios at Georgenhof willow and Wachtum. As total C stocks of the bulk soil did not change, C released by the decomposition of harvest residues replenished any possible SOC loss. The changes in the C fractions, as described above, indicated to a loss of soil organic carbon. But the high spatial variability of the harvest residues in the field made quantification of residue decomposition difficult and no influence of tillage depth or land use was detected. Nevertheless, at Georgenhof willow, loss of harvest residue C was lower in the deep compared to the shallow tillage depth. This was caused by less favourable conditions for the microbial biomass deeper in the soil as suggested by lower microbial C contents and lower microbial biomass C to SOC ratios in the deep in comparison with the shallow tillage treatments. At all sites, the higher C/N ratio of the harvest residues under grassland compared to arable use indicated to a slower decomposition, possibly due to a lower fungal biomass under grassland.

The results of the incubation experiment revealed the high N immobilization potential of the crown and root residues. Mineralization of easily available sources of the residues during first stages of decomposition caused a high N immobilization. Addition of inorganic N further increased N immobilization, but was lower for the larger sized residues. Increased ergosterol to microbial biomass C ratios after the addition of the woody the residues showed the

promotion of lignin degrading, saprotrophic fungi in the microbial community. The N addition seemed to lower the proportion of saprotrophic fungi. Regarding the higher lignin contents of the roots, this explained the increased C mineralization of only the crown residues after application of N.

In summary, the loss of LF-C, microbial biomass C and macroaggregate-C indicates to a loss of SOC one year after re-conversion of the tree plantations back to arable use. As the soil C fractions were not affected by the three tillage depths, no statement can be given if a reduced tillage depth may reduce the mineralization of soil organic carbon. But at both Georgenhof sites, grassland use provided a better stabilization of macroaggregate-C. An interpretation of management effects on residue decomposition and on soil C dynamics is difficult to make, due to the high spatial variability of the harvest residues in the field. The incubation study revealed the high N immobilization potential and the promotion of saprotrophic fungi after the incorporation of the harvest residues. N addition further increased N immobilization during early decomposition stages and lowered the proportion of saprotrophic fungi in the microbial community. Hence, N-fertilization in the field may not be appropriate until easily-degradable substances of the harvest residues are depleted.

9. Schlussfolgerungen und Ausblick

Die Ergebnisse ein Jahr nach der Rückführung der KUPs in konventionelle landwirtschaftliche Nutzung bestätigen durch erste C-Verluste aus den labilen Pools des Bodens die vermuteten Mineralisierungsverluste aus der organischen Bodensubstanz nach dem Umbruch. Zwar konnte die Annahme einer verminderten Mineralisierung durch eine reduzierte Bodenbearbeitung noch nicht nachgewiesen werden, eine nachfolgende Grünlandnutzung vermag jedoch das Ausmaß der Mineralisierung zu mindern.

Allerdings werden KUPs größtenteils auf ehemaligen Ackerflächen angelegt, so dass im Falle einer Rückführung auch wieder von einer ackerbaulichen Folgenutzung auszugehen ist. Daher sind weitere Untersuchungen insbesondere in den Ackerparzellen erforderlich, um die Auswirkungen einer regelmäßigen Bodenbearbeitung auf die Mineralisierung der organischen Bodensubstanz sowie der Erntereste zu untersuchen. Generell führt eine intensive Bodenbearbeitung zu einer höheren Mineralisierung der organischen Bodensubstanz gegenüber reduzierten Bodenbearbeitungsverfahren, so dass eine Reduzierung der Bearbeitungstiefe erstrebenswert erscheint. Da in der Praxis für die Landwirte die Ertragsleistung der Kulturen entscheidend ist, sei darauf hingewiesen, dass sich sowohl im Jahr des Umbruchs als auch im Folgejahr keine Ertragsunterschiede der beiden Nachfolgekulturen zwischen den drei Bearbeitungstiefen zeigten. Auch die Bewirtschaftung der Ackerflächen war in der flachen Frästiefe mit den für die Minimalbodenbearbeitung entwickelten Geräten problemlos möglich. Des Weiteren zeigte sich kein Austrieb der Pappeln oder Weiden aus den Wurzelstöcken, die nur in Tiefen von 5 und 15 cm zerkleinert wurden, so dass eine Reduktion der Frästiefe während des Umbruchs von KUPs sowie während der sich anschließenden Bodenbearbeitung der ackerbaulichen Nachfolgekulturen in der Praxis umsetzbar erscheint.

Das Belassen der oberirdischen Ernterückstände nach der letztmaligen Beerntung auf den Flächen und die nachfolgende Einarbeitung in den Boden können möglicherweise Mineralisierungsverluste der organischen Bodensubstanz im Zuge des fortschreitenden Abbaus der Erntereste mindern. Es sei allerdings darauf hingewiesen, dass solch hohe Mengen an Ernteresten nicht in KUPs für die Produktion von Energiehölzern mit kürzeren Ernteintervallen auftreten. Inwieweit der in den Ernteresten gespeicherte Kohlenstoff langfristig zum Aufbau organischer Bodensubstanz beitragen kann, muss in weiteren Untersuchungen geklärt werden und hängt maßgeblich davon ab, in welchen Bodenfraktionen die aus den Ernteresten freigesetzten Abbauprodukte stabilisiert werden.

Entgegen der ersten Vermutung eines verzögerten Abbaus der Erntereste in der tiefen Bearbeitungsvariante ein Jahr nach dem Umbruch, ist auf den tief bearbeiteten Ackerparzellen langfristig von einer schnelleren Mineralisierung gegenüber den weniger tief bearbeiten Parzellen auszugehen, da durch die regelmäßige, tiefe Bearbeitung Boden und Erntereste regelmäßig durchmischt und belüftet werden. Möglicherweise wird aber auch der Abbau der Erntereste durch eine tiefere Einarbeitung in den Boden im Zuge des tiefen Fräsens während des Umbruchs verlangsamt, wenn nachfolgend eine Grünlandnutzung oder nur eine reduzierte Bodenbearbeitung bei einer ackerbaulichen Nachfolgenutzung erfolgt.

Weiterer Untersuchungsbedarf besteht im Hinblick auf die Frage, ob die Einarbeitung hoher Mengen an verholzten Ernteresten infolge einer möglichen N-Immobilisierung, das nachfolgende Pflanzenwachstum negativ beeinflusst. Die steigende N-Immobilisierung nach N-Zugabe im Inkubationsversuch deutet an, dass eine N-Düngung erst nach Abbau der leicht verfügbaren Verbindungen der Erntereste empfehlenswert ist, um die Düngeeffizienz nicht herab zu setzen. Auf den Versuchsflächen wurden im Jahr sowie im Folgejahr des Umbruchs trotz einer reduzierten N-Düngung von lediglich 50% des ermittelten N-Bedarfs, keine signifikanten Ertragseinbußen gegenüber benachbarten, herkömmlich gedüngten Flächen festgestellt. Die heterogene Einarbeitung, der zum großen Teil nur grob zerkleinerten Erntereste, führte in keiner Bearbeitungstiefe zu negativen Auswirkungen auf die pflanzenverfügbare N-Menge. Dennoch stellt sich insbesondere die Frage, wie sich die unterschiedliche Verteilung der Erntereste im Boden, mit einer höheren Konzentration in oberen Bodenschichten in den beiden reduzierten Bearbeitungsvarianten und einer gleichmäßigeren Einarbeitung in den Boden nach tiefer Bearbeitung, langfristig auf die Menge an pflanzenverfügbaren N auswirkt.

Aufgrund der nur kurzen untersuchten Zeitspanne von einem Jahr nach der Rückführung der KUPs, kann abschließend noch keine Bewertung der Auswirkungen der unterschiedlichen Bearbeitungstiefen oder Nachnutzungen auf die C-Dynamik im Boden gegeben werden. Die Reduktion der Frästiefe beim Umbruch und dementsprechend auch die Reduktion der Bearbeitungstiefe während der nachfolgenden ackerbaulichen Bewirtschaftung, ist zur Verringerung des Abbaus der organischen Bodensubstanz als erstrebenswert anzusehen und in der Praxis umsetzbar. Allerdings müssen Untersuchungen in den folgenden Jahren erst zeigen, in welcher Weise ein nur flaches Einarbeiten der Erntereste deren Abbau, die N-Dynamik im Boden sowie die Ertragsleistung der Nachfolgekulturen langfristig beeinflusst, um eine Empfehlung für die Praxis geben zu können.

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