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Marina A. Anisimova
Jutta Rogasik
Ewald Schnug

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Carbon Balance of Waste Irrigated Forest Soils: A Case Study in North-West Germany

Marina A. Anisimova [1], Jutta Rogasik [2] and Ewald Schnug [2]

Abstract

Anthropogenic impacts such as waste water irrigation lead to potentially lower carbon storage in forest soils. The forest without irrigation is characterized by the highest storage of soil organic carbon with amounts of more than 200 Mg ha^{-1} C. The soils under irrigation contain about 90 Mg ha^{-1} C. Thus, carbon storage in irrigated forest areas is less effective in the long run than in non irrigated areas.

The anthropogenic input of organic carbon into soils was about 1.17 Mg ha^{-1} a^{-1}C. This input of soluble carbon substances with the irrigation water enhanced soil microbiological activity.

The leached carbon rises from about 3 to 20 $g{\cdot}m^{-2}{\cdot}a^{-1}$ C due to waste water irrigation. This indicates that the natural strong retention of dissolved organic matter within soil horizons is changed under anthropogenic impact.

The leaching of humic substances from soil contributes to the enrichment of well and stream water with organic carbon compounds.

The carbon sink potential of forest soils is decreased by 20 % as a result of anthropogenic waste water irrigation.

Compared with the large carbon pool of forest ecosystems the calculated amounts of leached carbon are not significant for carbon balances, but the risk of ground water pollution can not be ignored in this case.

Key words: forest, waste water, irrigation, carbon balance

Zusammenfassung

Kohlenstoffbilanzen für mit Abwasser beregnete Podsole - eine Fallstudie in Nordwest-Deutschland

Das Untersuchungsgebiet liegt in NW-Deutschland, vorrangig Nadelwald (*Pinus sylvestris*) gemischt mit Laubbäumen (*Acer platanoides, Betula pendula*) auf Podsol-Braunerde.

Untersucht wurde der Einfluß von Abwasserverregnung auf den TOC-Austrag aus Waldböden.

Anthropogene Einflüsse wie Abwasserverregnung führen zu potentiell geringerer C-Speicherung in Waldböden. Unberegnete Waldböden zeichnen sich durch eine höhere C-Akkumulation aus (>200 Mg ha^{-1} C) als beregnete (ca. 90 Mg ha^{-1} C). Die Verteilung des Kohlenstoffs im Bodenprofil wird vorrangig durch natürliche pedologische Prozesse bestimmt.

Der anthropogene Eintrag organischer Kohlenstoffverbindungen in die Böden des Untersuchungsgebietes durch Abwasserverregnung erreicht Größenordnungen von 1.17 Mg ha^{-1} a^{-1} C. Dieser C-Eintrag in den Boden über Zusatzwasser führt zu erhöhter mikrobieller Aktivität und damit zu verstärkter Umsetzung der anthropogen zugeführten Huminstoffe.

Das kalkulierte Austragsrisiko für Kohlenstoff steigt von 3 auf 20 $g{\cdot}m^{-2}{\cdot}a^{-1}$ C in Abhängigkeit von der Abwasserverregnung. Anthropogene Einflüsse verändern die natürliche Retention gelöster C-Verbindungen innerhalb der Bodenhorizonte.

Im Vergleich zum Gesamt-C-Pool ist die Menge der ausgetragenen Huminstoffe gering und damit nicht bilanzrelevant. Hinsichtlich Grundwassereutrophierung ist das Risiko des Austrages gelöster Huminstoffe aus dem Bodenprofil jedoch nicht zu vernachlässigen.

In anthropogen beeinflußten Waldökosystemen (Abwasserverregnung) wird das Senkenpotential der Böden für Kohlenstoff um ca. 20 % vermindert.

Schlüsselwörter: Wald, Abwasser, Verregnung, Kohlenstoffbilanz

[1] Laboratory of Soil Geography and Evolution, Institute of Geography, Russian Academy of Sciences, Staromonetny 29, 109017 Moscow, Russia

[2] Institute of Plant Nutrition and Soil Science, Federal Agricultural Research Centre, Bundesallee 50, D-38116 Braunschweig, Germany

1 Introduction

Soils are a major pool for organic carbon and play an important role in the global carbon cycle (Lal et al., 1997). Unsuited land use or soil management can contribute as a primary source of greenhouse gases (van Breemen & Feijtel, 1990; Esser, 1990; Bouwman & Sombroek, 1990; Tinker & Ineson, 1990). The assessment of the role of soils in the global carbon cycle is complex because soils usually contain inert fractions together with highly active microbial biomass as carbon sources (Körschens & Schulz, 1999). Thus, the estimation of turnover periods based on primary production or total soil carbon may bias the result (Schimel et al., 1994). The current carbon flux is regulated by the highly active fractions available usually in small amounts, while storage capacity is determined by the more stable and long-living fractions (Trumbore et al., 1990).

Anthropogenic carbon inputs may affect the C-flows and the driving variables for C-cycling in the soil system. Effluents resulting from food processing industry are generally rich in inorganic nutrients, such as N, P, and K, and in dissolved organic compounds. These products may pollute streams and lakes when improperly disposed. Using waste water containing organic substances for soil irrigation may

- enrich the soil with off-site organic substances, and
- remove natural soil organic matter resulting in Soil Organic Carbon (SOC) depletion.

Dissolved organic compounds may also reduce the oxygen content of soils and surface water resources, by increasing the oxygen demand.

The objectives of the case study described in this review were:

- to assess the effects of organic carbon inputs by irrigation water in native undisturbed soil, and
- to evaluate the changes in soil carbon leaching under the influence of irrigation.

2 Material and methods

The area selected for this investigation is a forest ecosystem under the influence of waste water irrigation. The experimental site is located in an area with low-fertile sandy soils dominated by coniferous forest (*Pinus sylvestris*) mixed with deciduous trees (*Acer platanoides, Betula pendula*) in the North-West of Germany. According to the FAO classification system (Roeschmann, 1986) the soils are classified as *Podzols*.

These soils are characterised by a relatively thick, slightly-decomposed litter layer, an acid reaction of the soil solution (pH≈4.5-6), a low content of plant nutrients and low microbiological activity with prevalence of decomposing organisms.

Tab. 1
Carbon sinks and sources for mixed coniferous / deciduous forest ecosystems in the temperate zone (C parameters compiled from literature)

Parameter		Unit	Range	References
Carbon-sink				
Vegetation(standing biomass C)		$Mg \cdot ha^{-1} C$	130 - 250	Lal et al., 1997; Johnson & Tod, 1997
Net primary production		$Mg \cdot ha^{-1} \cdot a^{-1} C$	2 - 10	Galinski & Kueppers, 1994; Brown et al., 1995; Killham, 1994; Johnson & Tod, 1997
Forest floor (litter)		$Mg \cdot ha^{-1} C$	30 - 150	Galinski & Kueppers, 1994; Rollinger et al., 1997; Johnson & Tod, 1997
Total soil C		$Mg \cdot ha^{-1} C$	100 - 300	Bouwman, 1990; Killham, 1994; Lal et al., 1997, Rollinger et al., 1997; Johnson and Tod, 1997
Average net annual rate of C accumulation		$Mg \cdot ha^{-1} \cdot a^{-1} C$	1 - 3	Bouwman, 1990; Johnson & Tod, 1997; Brown et al., 1995
Carbon-source				
Root and soil C respiration		$Mg \cdot ha^{-1} \cdot a^{-1} C$	3 - 8	Bouwman, 1990; Johnson & Tod, 1997
DOC	surface horizon	$mg \cdot l^{-1}$	56	Moore, 1997
	subsurface horizon		12	
	stream		5	
DOC	surface horizon	$g \cdot m^{-2} \cdot a^{-1}$	80	
	subsurface horizon		18	
	stream		**7**	
TOC	ground water	$mg \cdot l^{-1}$	8 - 19[1] 66 - 82[2]	Jopke and Schnug, 1995

[1] without irrigation
[2] with irrigation

Tab. 2
Anthropogenic input of carbon into forest soils (case study Germany)

C_{iw}	Average content of carbon in irrigation water	$g \cdot l^{-1}$	0.6
V_{iw}	Annual amount of irrigation water	m^3	150 000
S_{iw}	Forest land under irrigation	m^2	768 642
C_{anthr}	Anthropogenic input of carbon into soil with irrigation water	$g \cdot m^{-2} \cdot a^{-1}$	117

Carbon influx and efflux calculations were based on investigations of Jopke and Schnug (1995), Schnug (1996), and on literature data (Table 1).

The anthropogenic organic carbon input into the soils with irrigated waste water (Table 2) was calculated based on equation (1):

$$C_{anthr} = (C_{iw} * V_{iw})/S_{iw} \qquad (1)$$

where:

C_{anthr} anthropogenic input of carbon into soil with irrigation water [$g \cdot m^{-2} \cdot a^{-1}$]
C_{iw} average content of carbon in irrigation water [$g \cdot l^{-1}$]
V_{iw} annual amount of irrigation water [m^3]
S_{iw} forest land under irrigation [m^2]

Soil carbon storage was estimated based on soil samples (0-120 cm) from 3 different soil profiles (forest area without irrigation and forest area with irrigation on back and foot slope). Total organic carbon was determined by means of a LECO® EC-12 (method: dry combustion).

Tab. 3
Storage and distribution of soil organic carbon in forest soils (case study Germany)

Horizon	Depth [cm]	Soil organic carbon [%]	[$Mg \cdot ha^{-1}$]
1 Forest land without irrigation (Point 1)			
A_d	0 -5	5.54	27.7
AE	5 -20	5.81	104.6
EB_{fh}	20 -35	0.87	19.6
B_{fh}	35 -60	0.98	36.8
C_h	60 -90	0.49	22.1
D_h	90 -120	0.58	26.1
			Total: 236.8
2 Forest land under irrigation (Point 2, back slope)			
A	0 -20	1.62	45.4
AE	20 -30	0.48	7.2
EB_{fh}	30 -60	0.33	15.8
B_{fh}	60 -90	0.17	8.2
C_h	90 -120	0.29	13.9
			Total: 90.5
3 Forest land under irrigation (Point 3, foot slope)			
O/AE	0 -5	7.93	39.6
E	5 -30	0.11	4.1
EB_{fh}	30 -60	0.17	7.6
B_{fh}	60 -90	0.28	13.4
			Total: 64.9

3 Results and discussion

3.1 Sequestration of soil organic carbon in forest soils

Forests are expected to sequester carbon without explicit human intervention. The soil organic carbon content is a function of time, topography, parent material, vegetation and climate. Anthropogenic impact like the waste water irrigation can change the quantity of carbon stored. To take this fact into account, the organic carbon contents in the soil profiles were estimated (Table 3). The total organic carbon storage in the case study is in the expected range for this soil type (compare Table 1), and the distribution of carbon in the soil profile is predominantly determined by pedological processes.

The maximum soil organic carbon content was observed in the upper horizons (Table 3). The forest without irrigation is characterised by the highest storage of soil organic carbon with amounts of more than 200 Mg ha^{-1} C. The soils under irrigation contain 60-90 Mg ha^{-1} C.

Therefore the carbon storage in irrigated forest areas is less effective in the long run than in non irrigated. Waste water supply will lead to potentially lower carbon storage. The rates of decomposition vary due to differences in water content and the availability of nutrients. Simple substrates such as glucose (component of the analyzed waste water) are decomposed within weeks in the soil environments. Where soil processes are seasonally moisture limited, as was the case in the non-irrigated forest, a decrease of C mineralization takes place (see also Bottner et al., 2000). The soil-vegetation system acts as a sink of carbon.

Furthermore, the differences in the SOC pool on the field site may be explained by vegetation cover (Table 4).

Without the human intervention of supplying waste water in the forest area, the flux of carbon to and from the forest would be affected by natural factors only.

3.2 Carbon fluxes of a forest ecosystem

Net forest ecosystem production expressed as the carbon influx per hectare is calculated in the range of 6.0 Mg ha^{-1} a^{-1} C (without irrigation) up to 6.5 Mg ha^{-1} a^{-1} C (with irrigation) based on the data shown in Table 1. This C amount forms the nutrient pool for all important transformation and accumulation processes in the soil-vegetation system.

The amount of C respired by soil heterotrophs as CO_2 ranges between 70-80 % from net primary production.

Tab. 4
Causes of differentation in soil organic matter

Forest land without irrigation	Forest land with waste water irrigation
• timber forest • less light transmission • reduced turnover rates	• partly forest plantation • less canopy density • supply of readily soluble carbon substances with the irrigation water
➢ lower respiration rate, lower carbon losses	➢ higher respiration rate, higher carbon losses

Tab. 5
Soil organic carbon pool and carbon fluxes of a forest ecosystem (case study Germany)

Carbon pool and carbon fluxes		Forest ecosystem without irrigation	with irrigation
Organic carbon storage in soil	$Mg \cdot ha^{-1}$ C	230	90
Net primary production	$Mg \cdot ha^{-1} \cdot a^{-1}$ CO_2-C	6.0	6.5
Anthropogenic input with irrigation water	$Mg \cdot ha^{-1} \cdot a^{-1}$C	-	1.17
Respiration of heterotrophs	$Mg \cdot ha^{-1} \cdot a^{-1}$ CO_2-C	4.2	6.14
Carbon sink	$Mg \cdot ha^{-1} \cdot a^{-1}$C	1.8	1.53

Decomposition of soil organic matter will be enhanced when heterotrophic respiration increases as a result of more favourable climatic conditions or the availability of readily soluble carbon substances. The average net annual rate of C accumulation (C-sink), defined as the difference between net primary production and the amount of C respired by soil heterotrophs as CO_2 , ranges between 1.6-1.8 $Mg\ ha^{-1}\ a^{-1}$ C (Table 5).

Irrigation with waste water decreased the carbon sink by increasing respiration rates and by increasing carbon leaching (Tables 5, 6). The decomposition and transformation processes of carbon in soils under irrigation with sugar-containing waste water are more intensive due to increased microbiological activity caused by the supply of readily-soluble organic substances. Similar effects were observed by Franzmeier et al. (1985).

3.3 Calculation of the carbon leaching

In forests, humic compounds result from pedological processes and litter decomposition or humification. The dark-coloured, fine humic substances (predominantly fulvic acids) have a high mobility under humid climatic conditions. The efficiency of the microbial community in processing solutes in water varies with their composition and activity, which in turn vary with the abundance and composition of the organic substances that support microbial growth. Studies by Clinton (2001) relating dissolved organic matter (DOM) and microbial dynamics verify that a potential source of labile carbon is the vertical input from overlying riparian soils. These inputs may stimulate microorganisms and create hotspots of activity. Therefore waste water irrigation as described in this case study could be such a potential source of carbon leaching.

Carbon leaching calculations for this case study refer to investigations of ground water samples (Jopke und

Tab. 6
Calculation of the carbon leaching risk after streamflow studies of Reynolds und Thompson (1988) and long term water balance studies in the NW of Germany

rainfall [1]	irrigation	evapo-transpiration [2]	water loss values [3]	overland runoff / groundwater discharge	C-Input (irrigation)	TOC $_{GW}$	Carbon leached
$mm \cdot a^{-1}$	$mm \cdot a^{-1}$	$mm \cdot a^{-1}$	$mm \cdot a^{-1}$	$mm \cdot a^{-1}$	$g \cdot m^{-2} \cdot a^{-1}$	$mg \cdot l^{-1}$	$g \cdot m^{-2} \cdot a^{-1}$
900	0	-495	-180	225	0	14	**3,2**
900	195	-602	-219	274	117	74	**20,3**

[1] data base: Klimaatlas von Nordrhein-Westfalen, MURL, 1989
[2] data base: Hydrologischer Atlas der BR-Deutschland
[3] interception and changes in soil water

Schnug, 1995; Schnug, 1996), indicating that the removal of humic substances (total organic carbon: TOC) from the soils under irrigation is higher than from the non-irrigated soils:

	Content of total organic carbon (TOC)	
Forest area without irrigation	8 – 19	[$mg \cdot l^{-1}$TOC]
Forest area with irrigation	66 – 82	[$mg \cdot l^{-1}$TOC]

With data of long term rainfall, evapotranspiration, overland runoff and groundwater discharge values, leached carbon was calculated (Table 6). The calculation assumes an average pattern of climatic conditions. There is a significant effect between leached carbon and the magnitude of waste water irrigation. The leached carbon rises from about 3 to 20 $g \cdot m^{-2} \cdot a^{-1}$ C. This indicates that the natural strong retention of dissolved organic matter within soil horizons is changed under anthropogenic impact. Thus, irrigating water moving through soils would extract carbon. This leaching of humic substances from the soil contributes to the enrichment of well and stream water with organic carbon compounds (Table 6).

3.4 Carbon balance in the forest

The carbon balance describes the average net annual rate of C accumulation minus the calculated amount of leached carbon (Table 7). The ecosystem under irrigation is characterized by a lower surplus of carbon. The enhancement of soil microbiological activity, due to more favorable moisture conditions, and the supply of soluble carbon substances with the waste water have increased the turnover processes. The carbon sink potential of forest soils is decreased by 20 % as a result of this anthropogenic impact. Compared with the large carbon pool of forest ecosystems, the calculated amounts of leached carbon are not significant for carbon balances, but the risk of ground water pollution can not be ignored in this case.

This case study takes a step towards assessing the carbon balances of waste water irrigated forest soils. Transformation processes of carbon compounds under different climatic conditions will have to be examined further in future. Such studies need to assess the risks of DOC leaching in watersheds.

Tab. 7
Carbon balance of a forest ecosystem (case study Germany)

		with irrigation	without irrigation
C input	[$Mg \cdot ha^{-1} \cdot a^{-1}$ C]	7.7	6.0
C output	[$Mg \cdot ha^{-1} \cdot a^{-1}$ C]	6.3	4.2
carbon balance	[$Mg \cdot ha^{-1} \cdot a^{-1}$ C]	**+1.4**	**+1.8**

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