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The Swiss carbon balance: methods, state of reporting and research perspectives

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For the 1990–1998 period, Switzerland reported an annual sink strength of Swiss forests of 4500–6000 Gg CO_2. In its latest submission in 2000, newly available national forest inventory (NFI) data were used to refine earlier estimates. The same NFI data can also be used to provide extrapolations for the near future. No carbon sequestration values have been reported to date for forest soils. The Swiss government will provide funding for a number of research activities under the umbrella of COST E21, ranging from modeling studies of carbon storage in Swiss forests to an evaluation of joint implementation methods. These projects are described briefly.
Keywords. Carbon balance, Swiss forests, net carbon sink, forest inventory data, modeling, Switzerland.

1. INTRODUCTION

National communications (NC) to the United Nations Framework Convention on Climate Change (UNFCCC) have been submitted by Switzerland annually for the years 1994–1998, with the 5th communication for 1998 submitted in April 2000 (SAEFL, 2000)

As shown in **table 1**, according to the latest Swiss Greenhouse Gas (GHG) Inventory, 13.6% of the gross CO_2 emissions of 1998 were removed by forest growth, land-use change, and forestry measures (SAEFL, 2000). This fraction had increased slightly from ≈10% reported for 1990. The sink is caused mainly by the following two processes:

– increase in carbon storage of existing forests as a consequence of less intensive harvesting regimes;
– increase of the forest area by abandonment of agricultural land: between 1990 and 1997, the forest area of Switzerland increased by ≈330 km^2 (+3.0%).

The reporting of these values (**Table 1**) was done according to the revised 1996 IPCC Guidelines for National GHG Inventories (Volumes 1–3), but category 5c “Abandonment of managed lands” was included in category 5a “Changes in forest and other woody biomass stocks”. No data were reported under categories 5b “Forest and grassland conversion” because this process does not occur in Switzerland, and under category 5d “CO_2 emission and removal from soil”, although for the latter some estimates could be made and might be included in future submissions (see below).

The reporting was coordinated by the Swiss Agency for the Environment, Forests and Landscapes (SAEFL). The Swiss GHGI is derived from a nationwide database on air pollution according to CORINAIR (SAEFL, 1995), with data being compiled from a wide range of sources. Emissions that derive directly from energy use are calculated from national statistics on the total storage and use of energy. Traffic emissions are derived from a specific model under the auspices of the Swiss Federal Department for the Environment, Traffic, Energy and Communication (Dienst Gesamtverkehrsfragen, GVF) and a private company, Infras Ltd. Emissions from cement production are derived from the energy consumption reported annually by the cement industry. The methodology used for determining the effects of land-use changes and forestry practices are dealt with in more detail below.

Table 1. Summary of the Swiss GHGI (year 1998) according to the latest submission (SAEFL, 2000). All data are in Gg.

GHG	1 Energy	2 Industry	3 Solvents	4 Agriculture	6 Waste	Gross emissions	5 LUCF	Net emissions
CO_2	41,211	2,204	0	0	1,394	44,809	-6,109	38,700
CH_4	222	<1	0	140	64	426	0	426
N_2O	12	<1	<1	8	<1	21	0	21

Some of the data in CORINAIR have not been updated since 1995 and thus do not represent current values. An update every five years was planned, but SAEFL currently does not have the human resources to perform this task, which is a consequence of a drastic reduction of the size of SAEFL's Department of Air Quality Control. SAEFL is currently considering an "outsourcing" solution.

2. WORKING GROUP 1 RELATED ACTIVITIES (Inventory of C sinks and sources)

The following considerations focus on category 5 (Land-use change and forestry) of the GHGI. The Swiss NC1 through NC4 used a methodology for this category based on national statistics of forest land (Forststatistik), which were combined with growth increment data that are based on site index and stand age (Keller, 1978). The NC5 (SAEFL, 2000) uses a much improved method that is based on new data that have become available from two National Forest Inventories (NFIs), which were conducted in 1983–1985 and 1993–1995, respectively.

The NFI contains data on aboveground forest biomass, the areal extent of extensively managed forests, unproductive forests, degraded forests, expenditures for timber harvest, the fate of harvested wood, as well as the potential growth in different ecoregions and in different stand types. Also, from the two inventories changes over time of some variables can be estimated, including changes in biomass stocks and the area converted from managed land to forests.

NFI1 refers to 1983–1985. Aerial photography was used to determine the forested area. The aerial and the terrestrial sample plot grid were the same (1 × 1 km). NFI2 refers to 1993–1995. The terrestrial sample was reduced to a grid of 1.4 × 1.4 km, whereas the number of aerial sample plots was augmented to a grid of 0.5 × 0.5 km. Aerial photographs were used for determining the forested area and for stratification purposes. The precision (standard error of the mean, e) of this method is about 1%. The forested area has increased by about 4% from 1985 to 1995, and most of the new forest area can be found in the Alps, specifically in the southern Alps at higher altitudes (>1000 m).

Estimation of standing volume (e ≈ 1%), growth (e ≈ 1%), harvesting and mortality (e ≈ 3%) was done with a systematic grid of sample plots, each plot consisting of two concentric circles of 200 m^2 (where trees with a DBH ≥ 12 cm were recorded) and 500 m^2 (where trees with a DBH ≥ 35 cm were recorded), respectively. A terrestrial sample plot grid of 1 × 1 km was used in the first NFI, amounting to 10,975 plots (accessible forest without shrublands or "brushwood"). The sample plot grid was 1.4 × 1.4 km in the second NFI, amounting to 6,412 plots that cover the total forested area. Tree regeneration was recorded on a suplot, with two regeneration plots of 14 m^2 per sample plot.

From the primary variables that are measured on the NFI sample plots, many secondary variables can be calculated using allometric functions. Aboveground biomass can be estimated from single tree data, and a rough estimate of coarse root biomass was made from diameter at breast height using an allometric function that is specific for coniferous *vs.* deciduous tree species (Santantonio *et al.*, 1977). Fine root biomass was assumed to be a constant fraction (5%) of coarse root biomass (Perruchoud *et al.*, 1999a). Volume estimates per area are made using a double sampling for stratification algorithm (Köhl, 1994). In this procedure, an auxiliary variable (i.e., average tree height on a sample plot) is estimated from aerial photographs for stratification purposes.

Linear interpolations for specific years between the two NFIs can be performed, and these have been used for the Swiss GHGI (SAEFL, 2000). The third NFI is expected to begin in 2004, so that one inventory cycle covering the entire Swiss forest area is performed every 10 years.

Soil carbon storage (category 5d of the Common Reporting Format) was not assessed in the NFI and was not reported in the Swiss GHGI, except for the estimate of root biomass, which was reported under category 5a. In a unique combination of NFI data (Kaufmann, 2000a) and succession models (Bugmann, 1996, Perruchoud, 1996, Perruchoud *et al.*, 1999a), Perruchoud *et al.* (1999b) estimated the potential carbon sequestration of forest soils in the Alps across the 20th century, as follows:

– Above- and belowground biomass were estimated based on NFI data as outlined above.
– Litter production was estimated *a posteriori* based on tree-ring data for growth.
– Anthropogenic litter removal was accounted for based on published time series. Scenarios of litter production constructed from these data served as input for the decomposition simulation model FORCLIM-D (Perruchoud, 1996), which allows long-term simulations of species composition, carbon dynamcis and litter decomposition in forests of the temperate zone under variable climatic conditions. Perruchoud *et al.* (1999b) found that forest soils may contribute substantially to Swiss carbon sequestration, but the potential is relatively small (< 5%) compared to anthropogenic emissions (**Table 1**). Perruchoud *et al.* (1999b) suggest that Swiss forest soils accumulated another 1,280 Gg CO_2 y^{-1} in 1985, i.e. ≈27% of the total carbon that was sequestered by trees.

3. WORKING GROUP 2 RELATED ACTIVITIES (Analysis of forest management practices)

Based on the data of the two NFIs, an empirical large-scale scenario model was developed (Kaufmann, 2000b). A model for the growth of single trees and probabilities for silvicultural interventions were derived from the observational data. Besides a "Business-as-Usual" scenario, the implications of various management strategies can be investigated. The model operates with a decadal time step and can be used to estimate changes in growing stock, mean annual increment, total fellings and mortality during time periods of up to 40 years.

In the context of the initial publication of results from the second NFI, Kaufmann and Brassel (1999) provided scenario calculations of standing volume and growth for the year 2015 based on this empirical model. Four different management strategies were investigated:

– In the baseline scenario ("Business-as-Usual"), standing volume was found to increase from an average 354 $m^3 \cdot ha^{-1}$ in 1995 to 398 $m^3 \cdot ha^{-1}$ in 2015 (+12%).
– Under an extensification scenario, silvicultural interventions were assumed to be limited to protection forests, which resulted in an increase of growing stock and growth by 45% (to 514 $m^3 \cdot ha^{-1}$) and 15% (to 10.6 $m^3 \cdot ha^{-1} \cdot y^{-1}$), respectively.
– For an equilibrium of growth and cut in the year 2015, harvest would have to be augmented by 20% from 5,4$\cdot Mm^3 \cdot y^{-1}$ of merchantable wood to ≈6,5 $Mm^3 \cdot y^{-1}$.
– To reduce the growing stock by 2015 to a level that is comparable to that of neighboring countries (≈260 $m^3 \cdot ha^{-1}$), annual harvest would have to be augmented by 70% to ≈9,3 $Mm^3 \cdot y^{-1}$.

4. PERSPECTIVES AND RESEARCH NEEDS

Only national projects are reviewed here. The Swiss government will provide funding for a number of research activities under the umbrella of COST E21, ranging from modeling studies of carbon storage in Swiss forests to an evaluation of joint implementation methods. Ten project proposals were submitted to the Swiss Federal Office for Education and Science (SFOES), which are presented very briefly below. The order of presentations follows a thematic line: ecological studies that provide input for models, methods to improve the Swiss national assessment, material substitution projects and socio-economic studies including Joint Implementation (JI) and Clean Development Mechanism (CDM) projects (**Figure 1**). It does not reflect any preference in priority or importance.

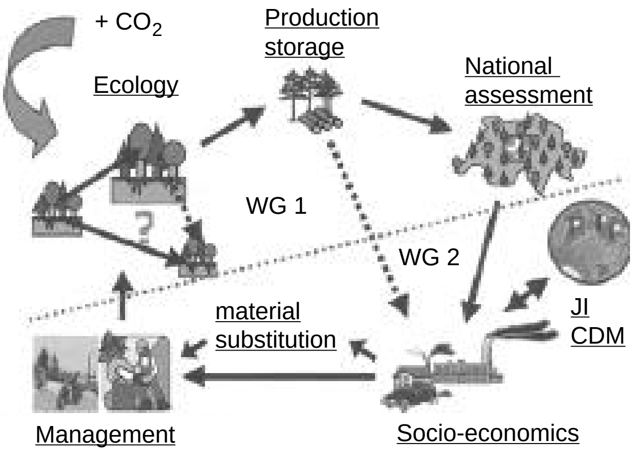

Figure 1. Overview of the thematic sectors that are covered by the proposed Swiss research projects in the context of COST E21.

1. *Recent growth trends in spruce and beech forests: roots, the hidden key players ?* (Bräker *et al.*) aims to use uprooted trees from the December 1999 storms to assess patterns of root growth and their potential contribution to mitigating CO_2 emissions.
2. *Response of N availability to atmospheric CO_2 enrichment in a mature forest* (Egli, Bucher) is concerned with elucidating the role of nitrogen limitation in a large CO_2 enrichment experiment (see project #3), which might limit the capacity of forest ecosystems to sequester C in a high-CO_2 world.
3. *Carbon binding of forests in a CO_2-rich world* (Körner) aims to document for the first time whether adult forest trees are limited by atmospheric carbon supply by enriching an entire mature mixed deciduous forest stand with CO_2 (Swiss Canopy Crane Project).
4. *Carbon pools and fluxes in Swiss forests: a quantitative assessment for the present and the 21st century* (Bugmann *et al.*) aims to perform a spatially explicit analysis of short- and long-term trends of CO_2 pools and fluxes in Swiss forests under a range of management scenarios.
5. *Development of dynamic model to establish the potential of carbon emission reductions through carbon substitution* (Richter, Hofer) proposes to analyze the potential of:
   – increased use of wood pro-ducts in the building and furniture industry,
   – improvements in the timber production process,
   – increased use of wood as biofuel.
6. *Biomass potential for bioenergy production, inclu - ding biofuel as a contribution to CO_2 mitigation* (Schlaepfer, Gnansounou) has a similar focus as project #5, with the general objective to improve

the scientific knowledge on the present and future availability of biomass to be used as biofuels.

7. *National baselines. Assessment of carbon fluxes in Swiss forests and use of wooden products. Transfer of methods to developing countries* (Schmidtke) addresses specifically the data needs for quantifying forestry-related carbon fluxes at the national level, and the potential for transferring these methods to developing country in the context of CDM projects.
8. *JI/CDM projects: quantification of the CO_2 effect of material and fuel substitution* (Kägi) is concerned with the additional CO_2 effects of JI/CDM projects, and aims to make suggestions on simple rules for calculating these effects caused by material and fuel substitution in JI/CDM projects.
9. *The effect of climate change and the Kyoto protocol on land use and forest management* (Kägi, Schmidtke) proposes to investigate the impacts that future economic policies will have on land use and forest management practices in Europe, emphasizing policies relating to the Kyoto protocol.
10. *Evaluation/validation and monitoring of JI/CDM forestry projects* (Schmidtke, Kägi) aims to develop standards and protocols for evaluating the effects of JI and CDM projects based on the significant earlier involvement of Swiss agencies in the debate and research on JI/CDM issues.

Although it has not been formally decided which of the above projects will eventually be funded, joint funding by SFOES and SAEFL is anticipated for 4–5 of the above projects, with a project start in late 2000 or early 2001.

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Bibliography

Bugmann HKM. (1996). A simplified forest model to study species composition along climate gradients. *Ecology* **77**, p. 2055–2074.

Kaufmann E. (2000a). Vorrat, Zuwachs, Nutzung. *In* Brassel P., Lischke H. (eds.). *Schweizerisches Landesforstinventar. Methoden und Modelle der Zweitaufnahme. Birmensdorf, Eidg. Forschungsanstalt für Wald, Schnee und Landschaft (WSL)*. (In press).

Kaufmann E. (2000b). Prognosen und Nutzungsszenarien. *In* Brassel P., Lischke H. (eds.). *Schweizerisches Landesforstinventar. Methoden und Modelle der Zweitaufnahme. Birmensdorf, Eidg. Forschungsanstalt für Wald, Schnee und Landschaft (WSL).* (In press).

Kaufmann E., Brassel P. (1999). Holzproduktion. *In* Brassel P., Brändli UB. (eds.). *Schweizerisches Landesforstinventar. Ergebnisse der Zweitaufnahme 1993–1995*. Bern: Haupt Publishers, p. 255–277.

Keller W. (1978). Einfacher ertragskundlicher Bonitätsschlüssel für Waldbestände in der Schweiz. *Eidg. Anst. Forstl. Versuchswes. Mitt.* **54**, p. 3–98.

Köhl M. (1994). Statistisches Design für das zweite Schweizerische Landesforstinventar. Ein Folgeinventurkonzept unter Verwendung von Luftbildern und terrestrischen Aufnahmen. *Mitt. Eidg. Forsch. Anst. Wald Schnee Landsch.* **69**, p. 1–141.

Perruchoud DO. (1996). *Modeling the dynamics of nonliving organic carbon in a changing climate. A case study for temperate forests*. Ph.D. thesis. Zürich, Switzerland: Swiss Fed. Inst. Technol. (Thesis; 11900), 197 p.

Perruchoud DO., Kienast F., Kaufmann E., Bräker OU. (1999a). 20th Century carbon budget of forest soils in the Alps. *Ecosystems* **2**, p. 320–337.

Perruchoud DO., Joos F., Fischlin A., Hajdas I., Bonani G. (1999b). Evaluating time scales of carbon turnover in temperate forest soils with radiocarbon data. *Global Biogeochem. Cycles* **13** (2), p. 555–573.

SAEFL (1995). *Vom Menschen verursachte Luftschadstoffemissionen in der Schweiz von 1900–2010*. Bern: Swiss Agency for the Environment, Forests and Landscapes. (Periodic publication; 256).

SAEFL (2000). *Swiss greenhouse gas inventory 1998. Common reporting format*. Bern: Swiss Agency for the Environment, Forests and Landscapes, 76 p.

Santantonio D., Hermann DK., Overton WS. (1977). Root biomass studies in forest ecosystems. *Pedobiologia* **17**, p. 1–31.

(12 ref.)

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