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ANALYSIS

Carbon sinks and human freshwater dependence in Stockholm County

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Abstract

People living in cities depend on the capacity of ecosystems to sustain their welfare. However, many services provided by ecosystems for city life are not perceived by people and policy. The city of Stockholm is growing and in that process natural capital is replaced by human-made capital. To visualize the dependence on natural capital of citizens in Stockholm County, we estimate the ecosystem areas required for accumulating the total emissions of CO_2 by the county's population. Stockholm County is inhabited by 1.8 million people and covers an area of ≈ 7240 km^2. Our results indicate that about 20170 km^2 of forest-, wetland- and lake-area is required to accumulate the CO_2 emissions of the population in Stockholm County. The Stockholm County ecosystems can potentially accumulate about 41% of the CO_2 generated by traffic and about 17% of total anthropogenic CO_2. We also estimate the amount of freshwater required to uphold a continued generation of ecosystem services in the county (*green water*). The ecosystems within Stockholm County require about 2.2 km^3 of green water per year to sustain the flow of ecosystem services, which is about nine times the direct human use of freshwater in households and industry (*blue water*). The potentially appropriated ecosystem area, if total CO_2 emissions from the population in Stockholm County were to be accumulated, would need more than 40 times the human blue-water appropriation. The green water appropriated by the ecosystems in Stockholm County is also indirectly appropriated by the human population through their dependence on ecosystem services. We discuss the usefulness and limitations of our approach in relation to focusing on people's dependence on functioning ecosystems for ecosystem service generation and in structuring guidelines for management of these ecosystems.

Keywords: Carbon sinks; Ecosystem services; Freshwater flows; Urban ecosystems

1. Introduction

Cities are important nodes of human activities. It is projected that as much as 60% of the global human population will live in an urban setting in

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2030 (UN, 1997). City inhabitants depend on ecosystems to produce food, water and other renewable resources. They also depend on ecosystems for the generation of clean air and the processing of waste (Folke et al., 1997). The role of natural capital in this context is seldom perceived (Jansson et al., 1994). Most of these services are hidden because they have no price in the economy, and people and policy seldom recognize them, but nevertheless they are real (Daily, 1997; de Groot, 1992; Odum, 1989).

Environmental problems of cities, such as air and water pollution and waste handling, are mainly addressed through conventional technologies that deal with point source pollution such as filters on chimneys, or construction of sewage treatment plants. The lack of understanding and appreciation of our dependence on ecosystem services causes human behavior and policy to push natural capital into becoming a scarce resource (Daly and Cobb, 1989; Jansson et al., 1994).

The city of Stockholm is growing through migration and industrial development and infrastructure and major roads being built. In that process, natural capital is reduced and transformed into human-made capital. The purpose of this article is to illuminate the role that ecosystems and ecosystem services play for city life and city development, and to illustrate some of the implications that follow from the fact that ecosystems do not function in isolation, but are connected through biological-, physiological-, and hydrological-flows and human activities. The citizens' dependence on freshwater in this context will be analyzed.

The article is divided into three sections. In the first section we (i) estimate the carbon (C)-accumulation potential of ecosystems in Stockholm County, and (ii) quantify the forest, wetland and lake areas needed to accumulate carbon dioxide (CO_2) from traffic, fossil fuel run electric power plants and other forms of combustion by the inhabitants of Stockholm County. We chose to quantify this ecosystem service in response to the results of the Kyoto Protocol, where it was concluded that Sweden is reducing more CO_2 than required, according to its quota (UNFCCC, 1997). The quantification will indicate whether or not natural capital inside the county will suffice to accumulate total emissions from the population of Stockholm County.

Ecosystem area analyses for cities have been done before but on a more general and much larger scale (Folke et al., 1996, 1997). The results of some earlier studies on the largest cities within the Baltic Sea drainage basin (14 countries with 29 cities $>250\,000$ inhabitants) indicate that the cities for their natural resource consumption and waste assimilation depend on an area of forest, agricultural, aquatic and wetland ecosystems that is 600–1200 times larger than the area of the cities themselves.

In the second section, we estimate: (i) the direct freshwater appropriation by the population in Stockholm County; (ii) the appropriation of freshwater by ecosystems in Stockholm County; and (iii) the amount of freshwater the inhabitants of Stockholm County would indirectly appropriate if total CO_2 emissions from the population were to be accumulated by surrounding ecosystems.

Freshwater assessments predominantly have focused on human use of run off or liquid water in rivers, lakes and reservoirs (Postel and Carpenter, 1997). The dependence on freshwater flows for a continued generation of ecosystem services is seldom addressed in policy, but has recently been estimated for the Baltic Sea as a whole (Jansson et al., 1999) and for the terrestrial biomes of the planet (Rockström et al., 1999). To put focus on the freshwater flows appropriated by ecosystems to uphold the generation of ecosystem services Folke and Falkenmark (1998) refer to the freshwater directly appropriated by the human population through extraction from rivers and aquifers as *blue water* and the water used by ecosystems to uphold the generation of ecosystem services as *green water*. From here on we will refer to the freshwater directly appropriated by the human population in Stockholm County, e.g. household consumption, industrial withdrawals, losses and general consumption, as blue water and the freshwater appropriated by the ecosystems in Stockholm County to uphold ecosystem service generation as green water. In the last section, we discuss the usefulness and limitations of our approach and results in relation to combining maintenance and development of city life with the management of ecosystems.

2. Estimating carbon-accumulation potential and appropriation of ecosystem areas in Stockholm County

Stockholm County is inhabited by 1.8 million people and covers an area of 7240 km^2 (Table 1, Fig. 1). The county is thus relatively densely populated with 275 compared to the Swedish mean of 22 persons per km^2 (Statistics Sweden, 1999a). Almost half the county area is covered by forests, dominated by Norway Spruce (*Picea abies*) and Scots Pine (*Pinus silvestris*). Stockholm County has rather few and small wetlands, only 110 km^2 (about 2%). Lakes and streams in the county cover about 10%.

2.1. Quantifying carbon-accumulation potential

2.1.1. Method

To estimate the net C-accumulation rate in above ground forest biomass in Stockholm County, the change in forest growing stock between years was calculated. The increase in Stockholm County forest growing stock between 1993 and 1997 was estimated at 4 mega forest cubic meter (Mm^3f) (Statistical Yearbook of Forestry, 1999). To convert from green weight (m^3f) to oven dry weight a factor of 0.43 was used (ton m^{-3}) (Pardé, 1980). A factor of 0.5 was used to convert from oven dry weight to C weight (Eliasson, 1996). Potential annual C accumulation in Stockholm County forests (CAP_f) was calculated according to Eq. (1):

$$CAP_f = CGS_f \cdot 0.43 \cdot 0.5/4 \quad (\text{ton C year}^{-1}), \qquad (1)$$

where CGS_f is the change in the forest growing stock between 1993 and 1997 (m^3f).

Average C accumulation in forest soils was estimated at 14.7 ton C km^{-2} per year (an average based on four different measurements in Swedish forests (Berg et al., 1995; Wardle et al.,

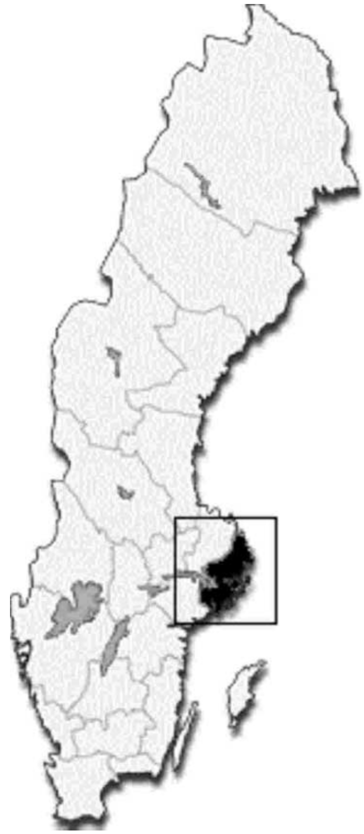

Fig. 1. Stockholm County, Sweden.

Table 1
Area of different land-use classes in Stockholm County

Land-use classes	Area (km^2)	Total area (%)
Forest land[a]	3030	42
Wetland[b]	110 (40)[c]	1
Nature reserve and military waste land[a]	120	2
Mountains[a]	820	11
Arable land[a]	890	12
Urban land[a]	1230	17
Grazing land[a]	190	3
Other land areas[a]	150	2
Water[d]	700	10
Total land and water area	7240	100

[a] Statistical Yearbook of Forestry (1999).
[b] Wetland Inventory in Stockholm County (1997).
[c] Figure in parentheses represents peat-producing wetlands.
[d] The lake area in the study does not include bays of the Baltic Sea or water bodies smaller than 0.1 ha (Statistics Sweden, 2001a). The Stockholm County part of Lake Mälaren is also included (Länsstyrelsen, Stockholm County, 1999).

1997)). Potential annual C accumulation in forest soils in Stockholm County (CAP_{fs}) was calculated according to Eq. (2):

$$CAP_{fs} = ACA_{fs} \cdot A_f \quad (\text{ton C year}^{-1}), \tag{2}$$

where ACA_{fs} is the average C-accumulation potential in forest soils (ton C km^{-2} per year) and A_f is the forest area (km^2).

Only peat forming wetlands (bogs and fens) in Stockholm County are included in the C-accumulation quantification for wetlands. Thus, only 36% of the wetland area in the county are included. Wetland peat growth in the Temperate Zone has been estimated at 21.4 ton C km^{-2} per year (Franzén, 1994). Potential annual C accumulation in wetlands (CAP_w) in Stockholm County was calculated according to Eq. (3):

$$CAP_w = PG_w \cdot A_{pw} \quad (\text{ton C year}^{-1}), \tag{3}$$

where PG_w is peat growth in wetlands (ton C km^{-2} per year) and A_{pw} is the peat growing wetland area (km^2). The average C accumulation in Swedish lakes has been estimated at 38 ton C km^{-2} per year (Eriksson, 1991). Potential annual C accumulation in lakes (CAP_l) in Stockholm County was calculated according to Eq. (4):

$$CAP_l = ACA_l \cdot A_l \quad (\text{ton C year}^{-1}), \tag{4}$$

where ACA_l is the average carbon accumulation in lakes (ton C km^{-2} per year) and A_l is the lake area (km^2). Anthropogenic CO_2 emissions from traffic, fossil fuelrun electric power plants and other forms of combustion in Stockholm County were estimated at 1.7 Mton C per year and traffic emissions alone at 0.7 Mton C per year (Miljöförvaltningen, Stockholm, 1997, 1996).

2.1.2. Results

C-accumulation potentials for forests, wetlands and lakes in Stockholm County are presented in Table 2. When comparing total C-accumulation potential for forests, wetlands and lakes in Stockholm County with CO_2 emissions generated within the county, our results indicated that these systems can accumulate about 17% of total CO_2 emissions and about 41% of the CO_2 emissions from traffic.

2.2. Estimating additionally appropriated ecosystem areas for accumulation of total CO_2 emissions

2.2.1. Method

All ecosystems in the county combined do not have the potential to assimilate total CO_2 emissions from the county population. We therefore estimate the additional ecosystem area required to accumulating remaining CO_2 emissions generated by the county population. As forests are the most efficient C-accumulating ecosystems in Stockholm County (Table 2), we chose to express the additional ecosystem area needed to accumulate remaining CO_2 as a forest area, in order not to overestimate the additional ecosystem area needed. Potentially appropriated forest area (A_{PAF}) to accumulate total anthropogenic CO_2 is calculated according to Eq. (5),

$$A_{PAF} = A_f/(CAP_f + CAP_{fs}) \cdot (CE_t - CAP_w - CAP_l) \quad (\text{km}^2), \tag{5}$$

where A_f is the forest area (km^2), CAP_f is the C-accumulation potential in above ground forest biomass (ton C year^{-1}), CAP_{fs} is the C-accumulation potential in forest soils (ton C year^{-1}), CE_t is the total carbon emissions from the population in Stockholm County (ton C year^{-1}), CAP_w is the C-accumulation potential in wetlands (ton C year^{-1}) and CAP_l is the C-accumulation potential in lakes (ton C year^{-1}).

Table 2
Annual C-accumulation potential by ecosystems in the Stockholm County

Ecosystem type	C-accumulation potential (ton C km^{-2} year^{-1})	C-accumulation potential (ton C year^{-1} × 10^3)
Forest (above ground biomass)	71.0	215
Forest (soils)	14.7	44.5
Wetland	21.4	1
Lake	38	27
Total		287.5

2.2.2. Results

If the remaining CO_2 were to be accumulated by forests, the citizens of Stockholm County would need about 16 400 km^2 additional forest area. A total forest area of 19 425 km^2 would be needed, which is equivalent to an area $\approx$6.4 times larger than the forest area available at present or to an area about 2.7 times the entire Stockholm County.

3. Human dependence on blue- and green-water flows

When estimating water appropriation by human society, focus is often on the water used directly in human activities for drinking, industrial purposes and agricultural irrigation (Gleick, 1993) (blue water). However, it is also of great importance to address the relationship between green-water flows and ecosystems in order to ensure a continued generation of ecosystem services. If this indirect freshwater dependence, through appropriation of aquatic and terrestrial ecosystem services, is not recognized, this freshwater resource is at risk of being regarded as unused or free and therefore redirected for other purposes.

3.1. Estimating the blue-water appropriation by the population in Stockholm County

3.1.1. Method

Blue water appropriation data for the population in Stockholm County include household consumption, industrial withdrawals, losses and general consumption (Statistics Sweden, 2001a). Water consumption through irrigation was excluded from the blue-water budget as this water is accounted for in the green-water budget through evapotranspiration by crops.

3.1.2. Results

Blue-water appropriation for all the municipalities in Stockholm County is presented in Table 3.

Table 3
Blue-water appropriation for the 25 municipalities in Stockholm County derived from Statistics Sweden (2001a)

Municipality	Blue-water appropriation[a] ($m^3 \times 10^3$ $year^{-1}$)
Botkyrka	7449
Danderyd	2652
Ekerö	1570
Haninge	5888
Huddinge	7762
Järfälla	5411
Lidingö	3754
Nacka	6321
Norrtälje	26423
Nynäshamn	7911
Salem	999
Sigtuna	5026
Sollentuna	6239
Solna	6067
Stockholm	110 885
Sundbyberg	3208
Södertälje[b]	15 239
Tyresö	3062
Täby	4556
Upplands-Bro	3070
Upplands-Väsby	3579
Vallentuna	1664
Vaxholm	767
Värmdö	2630
Österåker	2652
Total	244 784

[a] Includes water used in households, industry and other uses. Water used for irrigation of crops has been excluded.
[b] Södertälje municipality is now divided into Nykvarn and Södertälje municipality, but there is as of yet no data on water appropriation for Nykvarn municipality.

3.2. Estimating the green-water appropriation by ecosystems in Stockholm County

3.2.1. Method

Evapotranspiration data of forests and wetlands and evaporation data of lakes (Fig. 2) were obtained from a study on linking freshwater flows and ecosystem services appropriated by people in the Baltic Sea drainage basin (Jansson et al., 1999). Green-water appropriation by forests (GWA_f) in the Stockholm County was calculated according to Eq. (6):

$$GWA_f = ET_f \cdot A_f \quad (m^3\ year^{-1}), \tag{6}$$

where ET_f is the evapotranspiration by forests (mm year^{-1}) and A_f is the forest area (km^2). Green-water appropriation by wetlands (GWA_w) and lakes (GWA_l) was calculated correspondingly.

Agricultural land areas (A_a, in ha), yield data per area unit (Y, in ton ha^{-1} year^{-1}) and water use efficiency (WUE) for the different crops are presented in Table 4.

Yield data are based on yield estimates from 15 years back. Harvest (H) for the different crops was calculated according to Eq. (7).

$$H = A_a \cdot Y \quad (\text{ton year}^{-1}). \tag{7}$$

The green-water appropriation by agricultural land areas in Stockholm County was estimated according to Eq. (8),

$$GWA_a = H \cdot WUE \quad (\text{m}^3 \text{ year}^{-1}), \tag{8}$$

where H is the harvest (ton year^{-1}) and WUE is the water use efficiency (m^3 ton^{-1}).

3.2.2. Results

Estimated green-water appropriation by ecosystems in Stockholm County to uphold the generation of ecosystem services contributing to the welfare of the inhabitants of Stockholm County is presented in Fig. 3.

The forests, wetlands, lakes and agricultural ecosystems of Stockholm County depend directly on a flow of green water that is about nine times the direct human blue-water appropriation.

3.3. Estimating the green-water appropriation by potentially appropriated ecosystems for accumulating total anthropogenic CO_2 emissions

3.3.1. Method

Green-water appropriation by the potentially appropriated forest area (GWA_{PAF}) was calculated according to Eq. (9):

$$GWA_{PAF} = ET_f \cdot A_{PAF} \quad (\text{m}^3 \text{ year}^{-1}), \tag{9}$$

where ET_f is the evapotranspiration by forests (mm year^{-1}) and A_{PAF} is the potentially appropriated forest area (km^2).

The total indirect green-water appropriation by inhabitants of Stockholm County if total CO_2 emission would be appropriated by ecosystems inside or outside Stockholm County (GWA_{tc}) was calculated according to Eq. (10):

$$GWA_{tc} = GWA_{PAF} + GWA_w + GWA_l \quad (\text{m}^3 \text{ year}^{-1}), \tag{10}$$

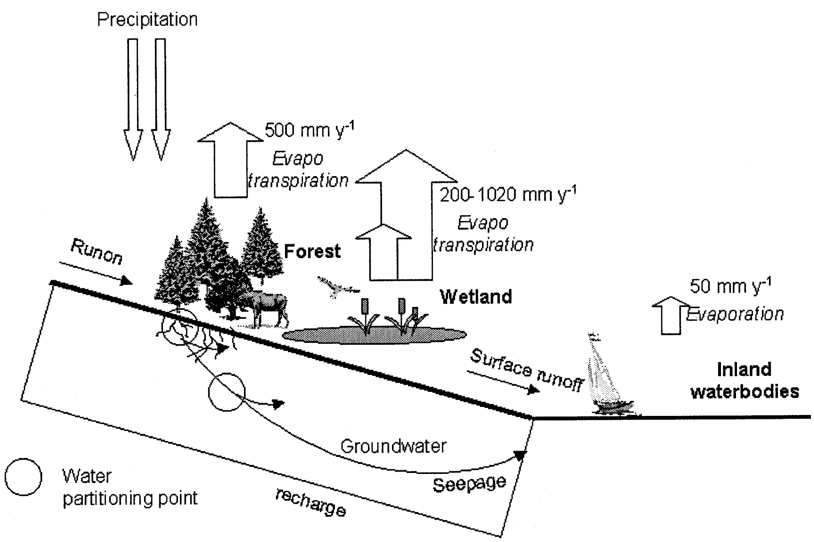

Fig. 2. The relationship between precipitation, runoff (blue-water flows) and evapotranspiration of forests and wetlands and evaporation of inland waterbodies (green-water flows). Evapotranspiration and evaporation data are based on literature data synthesized and presented by Jansson et al. (1999)

Table 4
Agricultural land areas, yield data per area unit and WUE for the different crops in Stockholm County

Crop	Land area[a] (ha)	Yield[b] (ton ha^{-1} $year^{-1}$)	WUE (m^3 ton^{-1})
Autumn wheat	14 640	5.996[c]	843[d]
Spring wheat	656	4.442[c]	843[d]
Rye	1759	4.719[c]	843[d]
Barley	14 553	4.321[c]	843[d]
Oats	11 941	3.732[c]	843[d]
Spring rape seed (vårraps)	662	1.561[c]	1748[e]
Spring rape seed (vårrybs)	1521	1.473[c]	1748[e]
Potatoes	101	18.999[c]	334[d]
Peas	1704	0.880[f]	424[d]
Ley lands	18 410	4.340[f,g]	758[d]
Rye wheat	1270	4.442[h]	843[d]
Mixed grains	527	3.732[i]	843[d]
Meadow	7708	4.340[j]	758[d]
Linseed oil	383	1.561[k]	1748[e]

[a] Statistical Yearbook of Agriculture (1999).
[b] Statistics Sweden (2000).
[c] Norm yield.
[d] Derived from Jansson et al. (1999).
[e] Derived from Bhan et al. (1980).
[f] Not norm yield.
[g] Data from 1997.
[h] Yield same as spring wheat.
[i] Yield same as oats.
[j] Yield same as ley lands.
[k] Yield same as spring rape seed (vårraps).

where GWA_{PAF} is the green-water appropriation by the potentially appropriated forest area (m^3 $year^{-1}$), GWA_w is the green-water appropriation by wetlands (m^3 $year^{-1}$) and GWA_l is the green-water appropriation by lakes (m^3 $year^{-1}$).

3.3.2. Results

If ecosystems inside and outside Stockholm County were to take care of total annual CO_2 emissions, the population in Stockholm County would indirectly appropriate about 10 km^3 green water per year.

4. Discussion

In this study we quantify a single ecosystem service, C accumulation performed by forests, wetlands and lakes in Stockholm County, to show some of the potential of ecosystems inside or in the vicinity of urban areas to generate services beneficial to the human population in that area. Our results indicate that forests, wetlands and lakes, which together cover about 53% of the county, can accumulate about 41% of the CO_2 generated from traffic and 17% of total CO_2 emissions from the population in Stockholm county. Although a majority of the ecosystems in Stockholm County potentially can act as carbon sinks and are able to accumulate almost a fifth of total anthropogenic CO_2 emissions in that area, an ecosystem area almost three times the entire county would be required to accumulate total CO_2 emissions. According to the Kyoto protocol, Sweden is reducing CO_2 emissions more than is required and has the right to increase their emissions by 4% (UNFCCC, 1997). Instead, Sweden has set a goal of reducing emissions by another 2% over a 10-year period through, e.g. increased taxes on fossil fuels and through subsidizing renewable energy sources (Swedish Climate Committee, 2000). This proposed line of action, if carried out, is encouraging and displays an effort to go beyond economic and equity concerns, to recognize the absolute necessity for every country to mitigate CO_2 emissions at maximum capacity in order to minimize the effects of greenhouse gases on our surrounding life-supporting biosphere.

Apart from the C-accumulating service, these ecosystems also provide the inhabitants of the county with a multitude of other services not addressed in this article, e.g. noise reduction, air filtering, micro climate regulation, rainwater drainage, sewage treatment, recreation and cultural values (Costanza et al., 1997; Bolund and Hunhammar, 1999). Many of the listed services are site specific and can thus not be performed by ecosystems located elsewhere. Also, the ecosystems in Stockholm County are subject to pressures through the growth of the city of Stockholm (Agency of Region Planning and Traffic, 2000).

To sustain a continued generation of services it is important to recognize that ecosystems depend on and are connected through water flows. Postel (1992) illustrates that redirection of water flows for increased crop production via irrigation has generated both quantitative and qualitative change in adjacent ecosystems. Few studies have been done that specifically show the connection between green-water flows and the generation of ecosystem services (although see Folke and Falkenmark, 1998, pp. 263–277Jansson et al., 1999; Rockström et al., 1999; Gordon and Folke, 2000). In this study we show that in order to accumulate the total CO_2 emissions generated by the population in Stockholm County an additional 16 400 km^2 of forest area would be appropriated. This additional forest area, together with present carbon sinks inside the Stockholm County, would appropriate about 10 km^3 $year^{-1}$ of green water, which is more than 40 times the human blue-water consumption in the county. Also, we show that in order to continuously benefit from the ecosystem services generated by the ecosystems located inside Stockholm County the human population of Stockholm County indirectly appropriate about nine times their blue-water consumption.

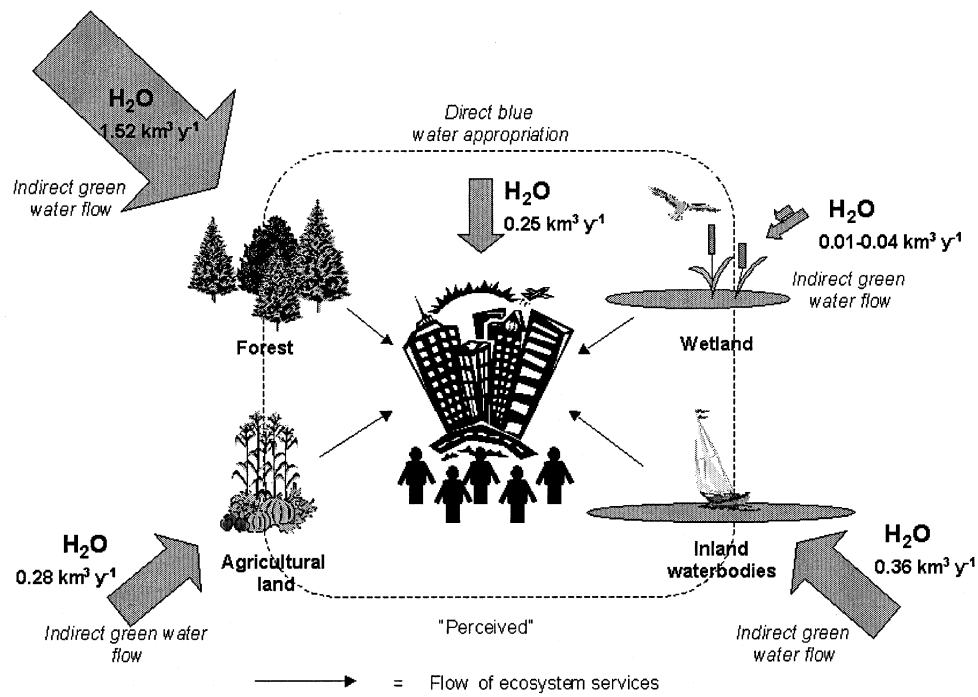

Fig. 3. Annual blue-water appropriation and indirect green-water appropriation, through appropriation of ecosystem services, by the human population in Stockholm County.

5. Conclusions

Our CO_2 footprint estimates show that urban ecological systems have a great potential for assimilating CO_2 emissions of the human population living in Stockholm County. However, they also show that these systems are not nearly large enough to assimilate total CO_2 emissions from the population living in the county. We recognize that the expectation that Stockholm County could assimilate total human-generated CO_2 emissions within the borders of the county is not a realistic one, as a county border is a political border not founded on any ecological basis of self-sufficiency. Also, Stockholm County has the highest population density of all Swedish counties (Statistics Sweden, 2001b). Nevertheless, our estimates still provide strong indications that current measures to mitigate CO_2 emissions are not sufficient and they thus render support for the line of action proposed by the Swedish government for a 2% reduction in emissions over a 10-year period.

Our quantification estimates on freshwater show that hydrological flows are not only of great importance for aquatic flora and fauna communities, for transportation of nutrients and for human direct consumption, but they are also crucial for sustaining the generation of ecosystem services that contribute to the welfare of the citizens of Stockholm County. In constructing management strategies designed to uphold ecosystem potential to provide ecosystem services, the fundamental role of green water in the generation of ecosystem services as well as the flows of blue- and green-water connecting ecosystems to each other must be taken into account.

The footprint estimates and quantification of blue- and green-water flows presented in this article are helpful tools in communicating the dependence of the Stockholm County population on surrounding ecosystems for providing ecosystem services that contribute to the welfare of the human population. However, our results say nothing about how the present extraction of ecosystem goods and services affects the ability of these systems to continue to deliver services. If our goal is to safeguard the systems' ability to generate services into the foreseeable future, we need to consider not only the size of the ecosystem areas appropriated by the human population, but also how the appropriated areas are responding to current levels of use or abuse, i.e. take into account the complex, self-organizing and dynamic nature of ecosystems (Levin, 1998).

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