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ENVIRONMENTAL ASSESSMENT OF ELECTRONIC PRODUCTS USING LCA AND ECOLOGICAL FOOTPRINT

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Abstract

The Ecological Footprint (EF) methodology, developed by Wackernagel and Rees, has often been suggested as a sustainability indicator for the human impact on earth. Efs, expressed as area, sum up the total productive area of land and water ecosystems required to sustain the resources, wastes, and emissions of a population wherever that land may be located. Thus, EFs can be established on a global or other geographic level. In this paper, we discuss whether the EF can be applied to electronic products. Based on a LCA study, we used a bottom-up approach for estimating the bioproductive space needed to appropriate the resources and emissions of a personal computer (PC). We also used area as a single indicator to make results comparable to the current terrestrial world-average footprint. Our estimates suggest that the EF of a PC is about 9 per cent of the terrestrial EF of a world-average citizen, which is probably underestimated. Although the results of this case study are a first approximation only, they indicate the magnitude of human appropriation of ecosystems by a single product.

1 Background

The key question behind the EF is whether nature's productivity is sufficient to satisfy present and future demands of the economy indefinitely. The EF method assumes that every category of energy and material consumption and waste requires the productive or absorptive capacity of a finite area of land or water [21]. The EF of a state or region sums up the biologically productive areas of consumption and waste absorption wherever on Earth that land or water may be located [10]. Previous studies based on United Nations statistics have shown that man's use of natural resources exceeds the earth's carrying capacity by more than a third [19].

If global biologically productive sea and land space on earth are divided by the global population, the average space per capita is 2.2 hectares (ha) per person. Without the sea, average land space is around 1.7 ha per capita [19]. The Brundtland Commission suggested a figure of 12 per cent for the other 10 to 30 million species on the planet, which might be politically feasible but will probably not be enough for securing long-term biodiversity [10]. From this, approximately 1.5 hectares per capita are left [20]. With an anticipated number of ten billion people by 2050, the available productive land and sea space will be reduced to 1.2 hectares world wide [20]. These figures are likely to be underestimated as to date, apart from CO_2, other emissions, toxins and wastes are not included in the calculations [21]. Recent work in EF assessments for products has been done by Buitenkamp and Spapens for a detergent and a photocopier [2]. In our case study, we tried to estimate how much bioproductive space is needed to appropriate the resources and emissions of a PC. We used a LCA based, bottom-up approach for matching our findings with the present, terrestrial footprint of a world-average citizen, based on [20]. This required aggregating the resources and emissions and appropriating these into area-units-equivalents.

2 Experiments

2.1 Methodology and assumptions for resource consumption

The data for this footprint analysis was taken from a LCA report on a generic PC from 1998 [1], carried out on behalf of the EC. The equipment was based on the assumptions shown in table 1. The impact assessment data was used for converting primary energy consumption into land space. The direct land-use data for the LCI materials was calculated from Frischknecht [7], which is mostly site-specific. Using the direct consumption of land space takes into account that even with recultivation measures after mining operations, the original environment with its species and habitats cannot be re-installed [17], Globally, recultivation efforts are very patchy due to the high costs involved [15].

200MHz CPU and cooler	Power supply
16MB EDO RAM	Mini tower cabinet
4 MB RAM graphics adapter	CD-ROM drive
3 GB IDE hard disk	15" SVGA colour monitor
3.5" floppy drive	Keyboard and mouse
Power consumption Monitor and Control Unit (incl. Keyboard)	100 and 60 Watts
Lifetime	3 years (230 days or 5520 hours)
Transport distance truck / van	525 km
Disposal routes Europe	63% land-filled, 22% incineration with 75% heat recovery, 15% recycling
Recovery rates metals	Steel 97%, Al 95%, other 100%

Tab. 1. Generic PC data according to [10].

The separate LCI inputs were appropriated to land areas. No generic assumptions can be made with regard to the land affected through mining operations, as they differ between mines and sites. Due to limited data available, we used data from mining sites, orebodies, density of materials, and overburden as a first approximation for the collateral impact from materials extraction. Overburden data was mainly collected from Douglas and Lawson [5], and Schmidt-Bleek [16]. Other mining data was mainly obtained from Frischknecht [7]. In our calculations the higher overburden values were used as they were sometimes given as an ore to commodity ratio, or included all material movements associated with extraction. An example is given in **Tab. 2**.

Material:	**Aluminium**	**Copper**	**Hard coal**
Land use (m^2/kg)	5.49E-04 [a]	6.41E-04 [a]	1.80E-04 [a]
Overburden factor:	3.68 [b]	450 [c]	4.87 [c]
[a] Calculated from FK 1996; [b] FK 1996; [c] DL 1998			

Tab. 2. Example commodities and their overburden.

For some raw materials the land space required for processing steps after the extraction phase could be included, such as for oil, coal, and natural gas. For gas and oil pipelines, space for infrastructure could not be established due to lack of data. The embedded energy was included in the LCA for all LCI inputs [14]. Some metals where found not to be included in the LCI, such as some Gold (0.8g), Silver (0.97 g), Beryllium (0.13g) and some Cadmium. Water was not included in this EF assessment, although we know from the LCA that approximately 74000 litres are consumed over a PC's life-time [1]. Therefore, land for resource consumption is believed to be highly underestimated.

2.2 Methodology and assumptions for estimation of CO_2 absorption areas

Fossil-energy-land is the land to be reserved for CO_2 absorption and refers to the spatial impact of fossil fuel use. As a minimum requirement, the fossil carbon added to the carbon cycle of the biosphere through burning must be sequestered if we assume that added anthropogenic CO_2 to the atmosphere should be curbed. This is, however, a strong sustainability assumption. Hence, the EF for fossil fuels is probably overestimated. Today, the only sequestering technique applied (and to a very limited extent) is growing forest that will not be harvested. Such land serves as a carbon dioxide sink during a period of 40 to 100 years, depending on climate and tree species. In order not to release the fixed CO_2, the mature forest would have to be maintained for the future without human intervention, spontaneously renewing itself. Harvesting is only possible with little wastage and if most of the biomass is transformed in long-lasting products [8]. To avoid increasing levels of CO_2 in the atmosphere in case of continued fossil fuel use, additional areas would have to be set aside for sequestration. These are not included in the calculations [20]. Here, a world -average carbon absorption of 1.42 tonnes per hectare and year including root mass, was applied, based on FAO data [20]. The latest data from the Intergovernmental Panel on Climate Change, IPCC [8, 9] have been used to calculate the fossil fuel specific carbon uptake by forests. No other terrestrial carbon sinks have been included so far. As oceans are a major sink for CO_2, they have been accounted for in the calculations. However, data for the amount of anthropogenic carbon which is fixed by the sea is based on complex models which can vary significantly. The Hadley Centre for Climate Prediction and Research at the British Meteorological Office assumes a figure of 25 to 33 per cent for anthropogenic carbon dioxide uptake by oceans [13] which is in line with the literature. However, should the oceans warm substantially, an opposite effect may counterbalance this absorption to some extent because warming water emits CO_2 into the air [12]. Here we used an absorption rate of 25 per cent of CO_2 per year. **Tab. 3** gives an overview on carbon absorption by forests per area. As other impacts such as acidification and eutrophication are not yet included in the calculations, the overall results are probably underestimated.

World average carbon absorption by forests:					
1.42 tonnes of carbon [t/ha/yr] including roots (Wac et al. 1999)					
	[a]CEF [t C/TJ]	GJ/ha/yr:	MJ/m^2/yr	**[b]NCV**	**MJ per m^2**
Crude oil	20	71	7.10	67	6.75
Coal	26	55	5.50	52	5.23
Nat.gas	15.3	93	9.30	84	8.37
[a] Carbon emission factors (IPCC 1997 a)					
[b] Net Calorific Values for fossil fuels: 95% of liquid and solid fossil and biomass fuels, 90% of natural gas (IPCC1997 a)					

Tab. 3. Fuel specific carbon absorption by forests.

3 Results and Discussion:

3.1 Land-use of resource consumption by PC system

By comparing the LCA amounts of resources with their respective land use, quantities and land-space do not change proportionally as overburdens are included for "non-renewables". This is especially visible in the case of copper with an overburden of 450 kg per kg copper derived from surface mining. Biomass was calculated as wood with a growth of 0.5 kg dry matter per m^2/year from IPCC data [8, 9]. The primary reason fossil fuels absorb so much space is related to the very high amount consumed. In the case of the keyboard, the relative high amounts of the raw materials crude oil and natural gas are due to the plastic ABS. The metals-to-plastic ratio is higher in the Monitor and Control Unit, which explains their higher presence in the land use data.

Tab. 4 shows the hierarchy for the top four resources from both studies. As these values represent the physical amounts taken from the earth only, and do not account for areas from associated wastes and emissions, these results are significantly underestimated. However, they serve as a valuable first approximation.

3.2 Land-space of resource consumption over a PC's life cycle

Fig. 1 shows the results for Monitor, Control Unit and Keyboard. For all three PC systems the material production determines the footprint-size with 53, 71 and 93 per cent. The use phase follows with 44 and 22 per cent of land consumption. Between 3 and 8 per cent of land-space are credited for recycling, which is 6 to 12 per cent of the space for material production. Land-space for material production was mainly determined by copper extraction, whereas fossil fuels determined the use phase.

It should be mentioned here that the credited land space is rather to be interpreted as space saved from further material extraction due to recycling, and not as a reconstitution of the original environment. Even if the environmental "rucksacks" are put back into the hole they have been taken from, they alter the sustainability of the area affected as they affect future erosion and slope stability of the respective site [4].

	LCA results	EF- results
Monitor	**1.** Hard coal, fuel **2.** Lignite, fuel **3.** Natural gas, fuel **4.** Crude oil, fuel	**1.** Crude oil, fuel **2.** Copper **3.** Hard coal, fuel **4.** Lignite, fuel
Control Unit	**1.** Hard coal, fuel **2.** Lignite, fuel **3.** Crude oil, fuel **4.** Natural gas, fuel	**1.** Unspecified bm f **2.** Copper **3.** Crude oil, fuel **4.** Wood, fuel
Keyboard	**1.** Hard coal, fuel **2.** Crude oil **3.** Crude oil raw m. **4.** Natural gas, r.m.	**1.** Copper **2.** Wood, fuel **3.** Crude oil, fuel **4.** Crude oil, raw m.

Tab. 4. Hierarchy of resources for LCA and EF.

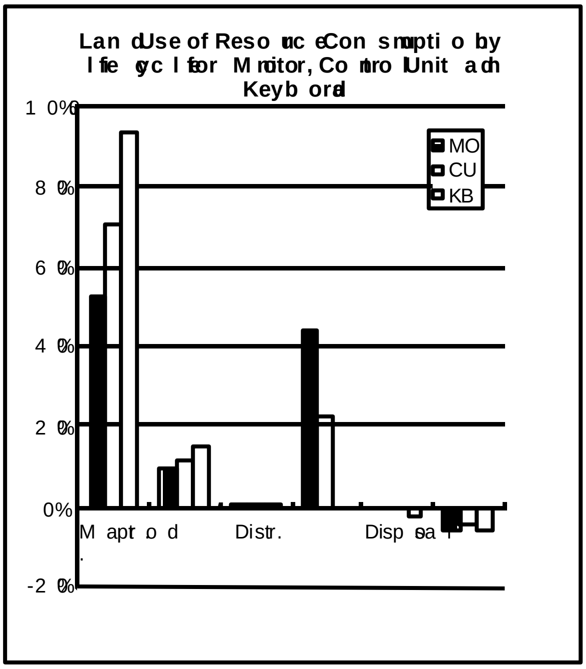

Fig. 1. Land use of resource consumption

3.3 Land-space for fossil-energy over life cycle

3.3.1 Materials-energy

Some fuel specific carbon emission factors and their appropriated space for CO_2-sequestration are shown in table 3. Because the overall results reflect the primary energy values from the LCA given in Mega Joules, the required land space for CO_2 sequestration is allocated pro rata.

If the primary energy for *materials* is appropriated into land space, the material production phase requires about 26 m^2, or more than 99 per cent of land-space in the Monitor, Control Unit and Keyboard. This reflects the relatively high energy costs in the extraction of non-renewable resources including the removal of overburden. However, land appropriated for materials energy only accounts for 1.5 per cent of the land for process energy.

3.3.2 Process-energy

Regarding *process* energy, the land-use is highest in the use phase for Monitor and Control Unit - it takes up 1340 m^2 (80 and 72 per cent). Manufacturing comes second with 340 m^2 (18 and 21 per cent for Monitor and Control Unit, 49 per cent for the Keyboard). Material production uses about 88 m^2 (3, 7 and 56 per cent). Around 9 m^2 are credited for recycling, which is 7, 12 and 3 per cent of material production, respectively.

Overall, the use phase consumes the lion's share of land-space for absorbing CO_2 emissions from material and process energy. Manufacturing consumes 25 per cent, and material production only 9 per cent of the land-space consumed for the use phase. Thus, the Monitor has the largest energy-footprint from use and manufacture (1070 m^2), followed by the Control Unit with 703 m^2, and the Keyboard with the smallest energy-footprint (15 m^2) from material production and manufacture. Including resource consumption, the EF of the total PC so far is 1790 m^2, or 0.18 ha. If 25 per cent of anthropogenic CO_2 emissions are absorbed by oceans, the PC's footprint on earth is still 1342 m^2 (0.13 ha) over its assumed life time of three years. **Fig. 2** and **3** show the energy footprints from materials and processes, and the overall results are summarised in **Tab. 5**.

Because CO_2-emissions associated with nuclear energy are low, it is sometimes suggested as a solution to global warming. However, there are reasons to consider nuclear energy as unsustainable [16].[1]

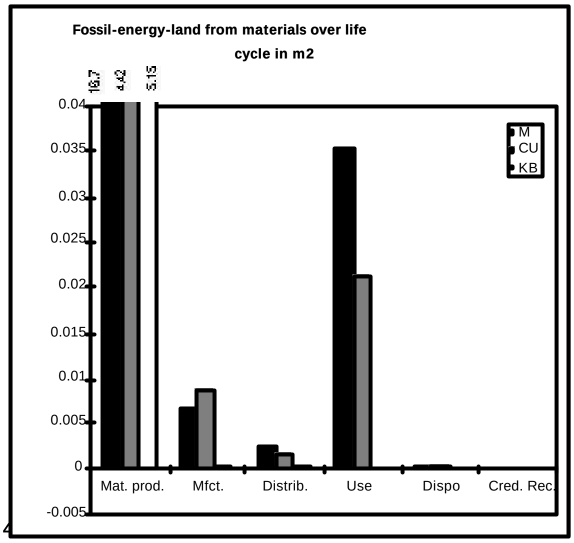

Fig. 2 Land-space from materials energy (Monitor, Control Unit, and Keyboard).

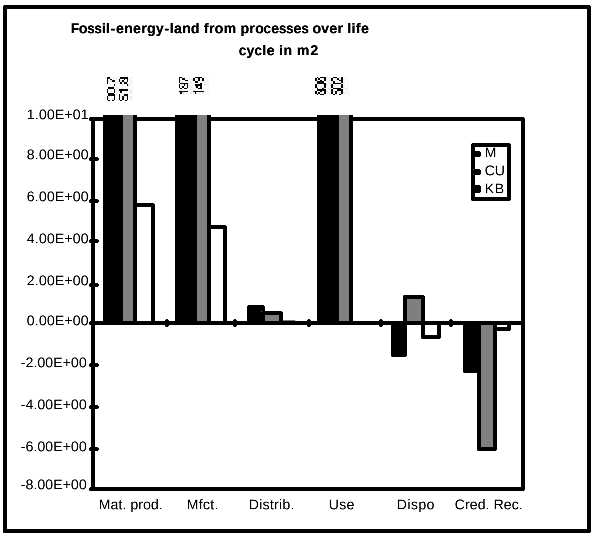

Fig. 3. Land-space from process energy (Monitor, Control Unit, Keyboard).

Totals (m2)	**Footprint res. cons.**	**Footprint energy**	**Ecological Footprint PC**
Control Unit	6.87E-01	6.99E+02	
Monitor	5.79E-01	1.07E+03	
Keyboard	3.27E-02	7.11E+00	
Total	**1.30E+00**	**1.77E+03**	**0.18 ha**

Tab. 5. Results and EF of a PC

IV. Summary and Conclusions:

In summary, a PC has a footprint of 1790 m^2, or 0.18 ha over its lifetime of three years. It exceeds its own physical size by more than a thousandfold. A PC's footprint is almost exclusively determined by fossil fuel use. This is about 9 per cent of the EF of the world average citizen, and is assumed to be very high for a single product in relation to other activities people pursue, such as heating, lighting, driving. However, these 9 per cent do not account for other outputs from resource consumption, such as emissions other than CO_2. This needs further investigation.

The results reconfirm the use phase as the main culprit, followed by manufacturing and material production. However, manufacture and material production account only for 25 and 9 per cent of the use phase, respectively. Using energy efficiency measures, for example the US EPA Energy Star requirements, could probably reduce the footprint size significantly.

The results also show that small amounts of resources extracted can have a high consumption of land-space, which was based on relatively high materials energy in the material production phase. However, this is offset by process energy in the use and manufacturing phase.

On the basis of the factors included in this study, the footprint from the resource consumption of raw materials appears to be negligible in comparison to the footprint from energy consumption. However, calculations suggest that at least 57×10^9 tonnes of material are dug from the earth's surface per year, of which 19.7×10^9 tonnes are minerals which are used, and 37.5×10^9 tonnes of which are waste or overburden. Apart from the energy associated with these material flows they also cause significant environmental site and off-site impacts [5, 18]. Ideally, these direct and indirect effects should be included in EFs.

At present, post-extraction data could only be included for a few non-renewable resources. Apart from overburden, no land use data was found for elements such as Gold, Silver, Tin, Lead and Zinc. They are present in PCs and have high environmental rucksacks, which must be seen in context with the impacts from global material flows. The study also shows that it is mainly the output side of resource use that creates pressures on the biosphere. Therefore, the present bioproductive space appropriated for the physical resource consumption can only be interpreted as a first approximation for the "hidden" areas required for impacts from materials extraction. The high amount of water consumed over the PC's life cycle (about 74000 litres) has not yet been appropriated into land area. This also suggests that the footprint for resource consumption is significantly underestimated.

Estimates of any heterogeneous process on a global scale are inevitably based on data with high uncertainties. Our estimates take a static snapshot of what is actually a highly complex dynamic ecosystem. But although not comprehensive, the results indicate the magnitude of human appropriation of ecosystems by a product. The EF for products can be very effective for giving an overview of a product's consumption in relation to a human's "fair earth share" as implied in the EF concept for populations. As an aggregate, single indicator, the EF communicates the resource consumption on a product level through links with the global level of world-average resource consumption. Used in this way, the EF holds the potential for measuring space-efficient technology. The EF does not compete with other assessment tools, but should rather be seen complementary. The above findings suggest that EFs have their role in the sustainability dialogue.

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These are for example problems and risks associated with uranium production from uranium-ore processing and reprocessing, and unsolved problems with the long-term storage of radioactive waste [7, 6, 11]. There are also political and economic objectives such as the global implication of nuclear energy with military use [11] and high capital and operation costs [22, 23]. Other studies show that a focus on nuclear energy inhibits the development of more sustainable energy sources [7]. Wackernagel et al. assume that nuclear energy has the same footprint as fossil energy: rough calculations suggest that the lost ecological bio-production caused by the Chernobyl accident compared to the total nuclear power produced since the 1970s leads to nuclear per [MJ] footprints larger than those of fossil fuel. As nuclear energy is not even economically competitive with fossil fuel, it will most likely be replaced in the short run with fossil fuel based energy [21]. If this is taken into account, the EF of the PC would increase by about 160 m^2, assuming a 12 per cent share of nuclear in an average European energy mix.