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Ecological Footprint as a tool for local sustainability: The municipality of Piacenza (Italy) as a case study

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ABSTRACT

The Ecological Footprint is a synthetic index useful to assess sustainability of anthropic systems. Its operational use, however, has been hampered by some difficulties, especially at a local scale. Being conceived as a measure of the biologically productive area requested to sustain individual consumptions in a human community, it leaves out the impacts associated to economic activities. Accordingly, the index cannot contribute much to define local policies, whose target are economic activities, and only marginally affect citizens' behaviour. Ecological Footprint calculation scheme can be modified to include the depletion of natural capital due to local activities such as industry, agriculture, tertiary sector, transport, waste and water management. We provide here an approach which takes into account these different aspects, while we discuss its application to a municipal area as a case study.

1. Introduction

The Ecological Footprint, (henceforth EF) measures the biologically productive area needed to sustain a certain human community (Chambers et al., 2000b; Rees, 1996; Wackernagel and Rees, 1996; Wackernagel and Silverstein, 2000) or process (De Leo et al., 2001). Because of its intuitive meaning and easiness of computation it has rapidly taken ground as a tool for assessing the human pressure on natural resources and ecosystem services. Its recent inclusion in the European Common Indicators Programme (ECIP) confirms the importance assigned to this index (Simmons, 2003). In Italy EF has been calculated for regions, provinces and municipalities (Ambiente Italia, 2001a,b; WWF Italia, 2000, 2002a,b). EF has become matter of interest because the impacts it measures, identified as exploited areas, may help define targets for remedial actions. Accordingly, it is perceived as a tool that helps to set up an agenda for local policies. However, its potential in this respect remains to be clarified. EF, in fact, is usually computed using the household Ecological Footprint scheme (Wackernagel et al., 2000, 2003) and this makes assessing certain impacts difficult. Consider, as an example, the impact due to electricity consumptions. EF quantifies the intensity at which the citizens use electricity, which, in turn, depends on everyone's lifestyle. Electricity is produced by power plants which emit CO_2, and a certain amount of forested land is thus required to absorb these emissions. In principle, this land requirement is shared among all the citizens who use electricity, and contributes to build up their EF. In general, they belong to different communities. However, the administrations which govern the territories that host the power plants are politically responsible for the emissions produced. To curb them they must take actions and cannot rely on educational programs launched by other local administrations whose communities use the energy produced by the power plants.

This example highlights that whether EF has to be of some help to local administrations, it must produce a reliable picture of what happens on the territory of their jurisdiction, and this includes impacts due to both citizens and productions. Of course, local authorities can (and should) do a lot on the side of environmental education but their political commitment is mainly targeted on economic activities or productions that takes place in their territory. Local policies aiming to sustainability must thus deal with these latter impacts and EF, to be effectively used to monitor the progress towards sustainability, must account for land requirement to sustain local activities. In this paper, while we discuss the case of the municipality of Piacenza (Northern Italy), we consider this dual aspect of EF and extend the spreadsheet of calculation accordingly. In particular, we make a conceptual and structural distinction between the Citizen Footprint (henceforth CF) and the Territorial Footprint (henceforth TF). The former includes the demand for natural capital to provide goods and services to sustain people's lifestyle, whereas the latter identifies and calculates the impact on natural capital of local economic activities and public services. This approach is not, however, merely a new calculation scheme: it produces two indices that are conceptually different and must be calculated separately, although together they provide a realistic picture of the impact a human community exerts on the environment.

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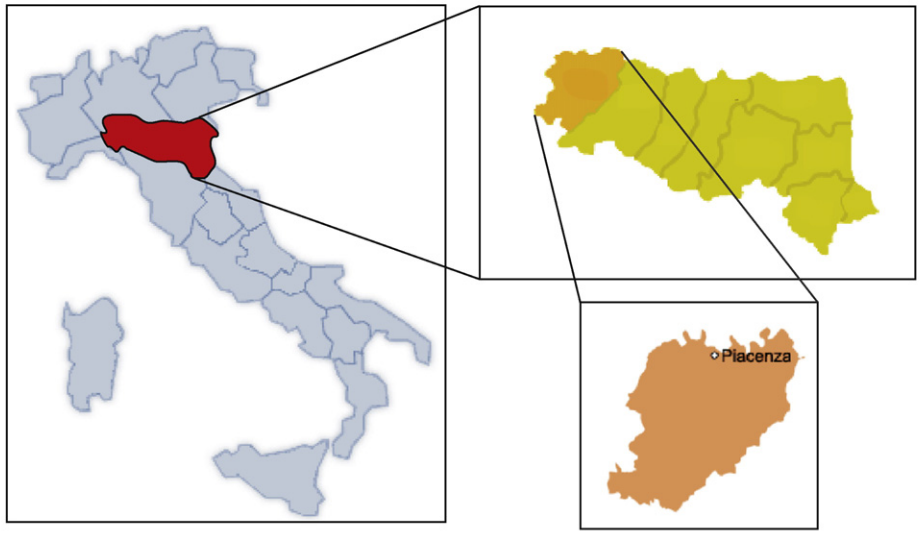

Fig. 1. Location of the study area in the Italian context. Piacenza is the capital of its province which is located within the Emilia Romagna region (Northern Italy).

While we present our methodological approach to EF we discuss also some important issues concerning its calculation. If this index has to be usefully employed in support of local policies, which imply decisions and effects at the different layers of the administrative hierarchy, homogeneity is required in the way it is calculated so that information can be shared about constraints and priorities for action. Presently, there are studies based on the spreadsheet of Ecological Footprints of Nations (Loh et al., 1999, 2000, 2002, 2004; Monfreda et al., 2004; Wackernagel et al., 1997, 1999a,b), others that use the household Ecological Footprint (Chambers et al., 2000a; WWF Italia, 2000, 2002a,b) and projects combining both approaches (Wackernagel, 1998). Moreover, within the same scheme of calculation there are differences as for type of categories considered and conversion factors adopted to transform impacts into global hectares (gha). Undoubtedly, a unique approach to calculation is prerequisite for EF to become an effective tool for governance.

2. Methods

Land requirement that makes up the EF is apportioned to six main area types: (a) cropland (crops for food, animal feeding, fibre and oil), (b) grazing land (to produce meat, hides, wool and milk), (c) forest area (e.g. harvesting trees for timber or paper making and gathering fuelwood), (d) fishing ground (fish for human consumption), (e) built-up land (e.g. areas occupied by infrastructures for industrial activities, transportation and housing) and (f) CO_2 area (the forest area needed to absorb CO_2 from combustion processes — see Appendix A) (Wackernagel and Monfreda, 2004). The extension of each area type required to sustain consumptions of resources or goods is obtained dividing their amount by specific coefficients of production:

$$\mathrm{Area}_i(\mathrm{ha}) = \frac{\mathrm{Consumption(t)}}{\mathrm{Yield}\left(\mathrm{t\ ha^{-1}}\right)} \tag{1}$$

In Eq. (1), i stands for the ith area type and Yield is the number of tonnes per hectare (t ha^{-1}) used to compute the area required to get each Consumption (t) from the land type i. Then, any Area$_i$ calculated corresponds to a consumption pattern.

Area types are summed up to obtain the EF value. To make this calculation consistent on a global scale, the value obtained for each land type is converted into global hectares (gha), a standardized unit of biologically productive area that is characterized by an ideal productivity equal to the average of the whole 11.4 billion bioproductive hectares (ha) on earth. This is done by using specific Equivalence Factors, that is

$$\mathrm{EF(gha)} = \sum_{i=1}^{n} \mathrm{Area}_i(\mathrm{ha}) \cdot \mathrm{Equivalence\ Factor}_i\left(\mathrm{gha\ ha^{-1}}\right) \tag{2}$$

where n stands for the total number area types (n=6).

Equivalence Factor for cropland is 2.17 gha ha^{-1}, meaning that 1 world average cropland hectare produce 2.17 times more than 1 global average bioproductive hectare (gha ha^{-1}) (2) (Wackernagel and Rees, 1996).

Biocapacity (B) quantifies productive land at disposal and it is computed as

$$B(\mathrm{gha}) = \sum_{i=1}^{n} \mathrm{Area(ha)} \cdot \mathrm{Equivalence\ Factor}_i\left(\mathrm{gha\ ha^{-1}}\right) \cdot \mathrm{Yield\ Factor} \tag{3}$$

in which the Yield Factor (Wackernagel and Rees, 1996), specific for each area type, relates local productivity to world average productivity (i.e. Yield Factor bigger than 1 means that local productivity is lower than global average productivity). Ecological Footprint is then subtracted from Biocapacity to establish whether the community runs an Ecological Deficit (4).

$$\mathrm{Ecological\ Deficit(gha)} = \mathrm{Biocapacity(gha)} - \mathrm{EF_{Comsumption}(gha)} \tag{4}$$

Our approach to EF integrates the classical Citizen Footprint with an estimation of the natural capital needed to maintain local productive activities, the Territorial Footprint. We applied this scheme to the municipality of Piacenza located in the industrialized area of the Po river plane in Northern Italy (Fig. 1).

2.1. Citizen Footprint

Individual consumptions were allocated into five categories: (a) food, (b) shelter, (c) mobility, (d) goods and (e) services (Global Footprint Network, 2005a; Lewan and Simmons, 2001). As for food consumption (annual per-capita kilograms), quantities were estimated from per-capita expense (€) (National Institute of Statistics — ISTAT[1]; The family consumption — Yearbook 2002) and average market prices

[1] www.istat.it.

(€ kg^{-1}). Transformation into global hectares of impacted land considers energy land, for all items, plus cropland, grazing land and fishing ground, depending on the specific origin. Shelter category comprises, mostly, domestic energy use. That is, household consumption of electricity (kWh) (National Transmission Net Manager — GRTN[2]; Electric energy consumption for merchandise sector database — year 2002), methane (m^3) and heating oil (l) (data provided by Piacenza municipality). Liquid gas and biomass have been excluded from calculations because their use and impact were negligible in comparison with patterns of energy types described above. This category contributes to EF as energy land and built-up area (in global square meter, henceforth gm^2); data were collected as m^2 from land register (Piacenza municipality[3]).

Mobility distributes its impact upon two area types: energy land, needed to absorb fossil fuel emissions by private cars (Italian Motor vehicles Club — ACI[4]; Circulating vehicles in Emilia Romagna municipalities) or public means of transport (e.g. bus and train energy consumption described by the Annual report of the Emilia Romagna public transport[5]), and built-up land (roads and infrastructures; Piacenza municipality[3]).

Good consumptions (annual per-capita kg), alike food category, were estimated from average per-capita expense (€) (National Institute of Statistics — ISTAT[1]; The family consumption — Yearbook 2002) and average market prices (€ kg^{-1}). Items in this category build up EF as energy land plus cropland, grazing land and forest productivity.

Services mostly impact on energy land (electricity[2] and fossil fuel) and built-up land (gm^2) for buildings. Details related to the consumption categories are reported in Table 1.

The most recent spreadsheet (Global Footprint Network, 2005a) has been adopted as a guideline in this study, so we did not treat waste production as a separate component of the household Footprint, as in the previous versions developed by Wackernagel et al. (2000, 2003) (versions 2.0 and 3.2). This item enters as a part of the life cycle of goods or as a management component of services.

Consumptions of the five different categories (e.g. kg of food, kWh of electricity and methane m^3) were then assigned to the six bioproductive area types, depending on origin and characteristics of the various items. All the contributions to the same area type were summed up and divided by the number of inhabitants to obtain a per-capita EF value. All the conversion factors (such as embodied energy, global yield of primary products, global conversion efficiency from primary to secondary products, CO_2 carbon absorption rate of forests, percentage of CO_2 absorbed by ocean) were available in the version 3.2 of the excel spreadsheet developed by Wackernagel et al. (2003).

2.2. Territorial Footprint

Four main categories were considered: (a) productive activities, (b) transportation, (c) waste disposal and management and (d) water management. Productions were further divided by sectors — e.g. industry, agriculture, and tertiary sector. Energy land, area for infrastructures, cropland and grazing land share this EF. Energy consumption for this category comprises electricity (National Transmission Net Manager — GRTN[2]; Electric energy consumption for merchandise sector database — year 2002), and fossil fuel utilization. Agriculture contributes to EF by cropland, grazing land, as well as energy land, including embodied energy of pesticides and fertilizers (National Institute of Statistics — ISTAT[1]; Database of fertilizers and fitosanitary products in agriculture).

Transportation distributes its impact over two area types: energy land needed to absorb emissions and built-up land for road development. Data to calculate the former contribution include fuel consumptions by cars, buses and trains, trucks and lorries, fuel for agricultural activities (e.g. ploughing, harvesting, irrigation of fields). All these information were provided by municipal offices as well as the statistical offices of the region Emilia Romagna[5]. Cross-border impacts are taken into account assuming the compensatory effect of vehicles fuelling outside the municipality boundary but consuming inside, and vehicles fuelling within the Piacenza city and travelling outside.

Energy land and built-up land were the two categories by which waste management contributes to EF. Data about non-domestic wastes, as well as household wastes, were provided by the Regional Agency of Environmental Protection (ARPA[6]; Household waste production in Piacenza Province — year 2002).

Energy used by the sewer system, for water purification (TESA Piacenza S.p.a.[5]; sewerage system management), and the management of water distribution (TESA Piacenza S.p.a.[5]; aqueduct consumptions) make up EF of the water management system. Table 2 summarizes all the categories that contribute to Territorial Footprint.

TF is expressed as total global hectares (gha) because production cannot be intended in terms of individual contributions.

The main conversion factors we adopted both in Citizen and Territorial sections are: embodied energy from Wackernagel et al. (2003) data, carbon absorption rate equals to 0.95 tC ha^{-1} $year^{-1}$ and 65% as the percentage of CO_2 absorbed by oceans.

3. Results

3.1. Citizen Footprint

The average per-capita Footprint equals to 3.794 gha cap^{-1} with the following contributions: 2.220 gha cap^{-1} of energy land, 0.913 gha cap^{-1}

Table 1
List of categories included into the Citizen Footprint calculations

Categories in Citizen Footprint
1. Food
• Bread and cereals (bread, bread sticks and crackers; biscuits; pasta and rice; cakes; other)
• Meat (beef; pork; chicken, turkey and rabbits; sausages; others)
• Fish
• Milk, cheese and eggs (milk; cheese; eggs; other)
• Oils and fats (olive oil; other oils and fats)
• Potatoes, fruit and vegetable (fruits; potatoes and vegetables)
• Sugar, coffee and spices (sugar; coffee, tea and cacao; ice creams; other)
• Beverages (wine; beer; other)
2. Shelter
• Electricity consumption
• Heating (methane; heating oil)
• Built-up area (houses and apartments)
3. Mobility
• Fuels (petrol; diesel oil; propane liquid gas; methane)
• Built-up area (roads, highways, parkings, railways and other travel facilities)
4. Goods
• Tobacco
• Clothes and shoes
• Furnitures
• Household appliance
• Detersives and detergents
• Linen and kitchenware
• Medicines
• Means of transportations
• Books and newspaper
• Personal computer, TV, radio and Hi-Fi
• Others
5. Services
• Electricity consumption
• Heating (methane; diesel oil)
• Built-up area (hospitals, barracks, cinemas, theaters, etc.)

2 www.grtn.it/ita/index.asp.
3 Town Planning Scheme - PRG.
4 www.aci.it.
5 www.regione.emilia-romagna.it.
6 www.provincia.pc.it.

Table 2
List of categories included into the Territorial Footprint calculations

Categories in Territorial Footprint
1. Productive activities
• Industry
–Electricity consumption
–Fossil fuels (methane; diesel oil; combustible oil)
–Industrial area
• Agriculture
–Electricity consumption
–Soil use (built-up area; cropland area; pasture area; embodied energy in fertilizers, pesticides and herbicides)
• Tertiary
–Electricity consumption
–Fossil fuels (methane; heating oil)
–Built-up area
2. Transportation
• Cars, buses and trains
–Petrol consumption
–Diesel oil consumption
–Propane liquid gas consumption
–Methane consumption
• Trucks and lorries
–Petrol consumption
–Diesel oil consumption
–Propane liquid gas consumption
–Methane consumption
• Agricultural fuel
–Diesel oil consumption for nursery gardening
–Diesel oil consumption for transportation
• Roads and facilities (highways, railway, bus and train stations, etc.)
3. Waste disposal and management
• Special wastes (dangerous and not dangerous)
• Household wastes (wastes, and fossil fuel consumption for waste transportation)
• Truck diesel fuel
• Built-up areas (dumps, incinerator, etc.)
4. Water management
• Sewerage system
• Purification water plant
• Aqueduct

of cropland, 0.302 gha cap^{-1} of fishing ground, 0.151 gha cap^{-1} of grazing land, 0.147 gha cap^{-1} of forest and 0.057 gha cap^{-1} of built-up land. Fig. 2 translates these fractions in percentage.

As for consumption categories, 49% of EF is due to food requirements (1.856 gha cap^{-1}), shelter is responsible for 15% (0.555 gha cap^{-1}), mobility 12% (0.467 gha cap^{-1}), goods 15% (0.573 gha cap^{-1}) and services 9% (0.344 gha cap^{-1}). These data are summarized in Fig. 3.

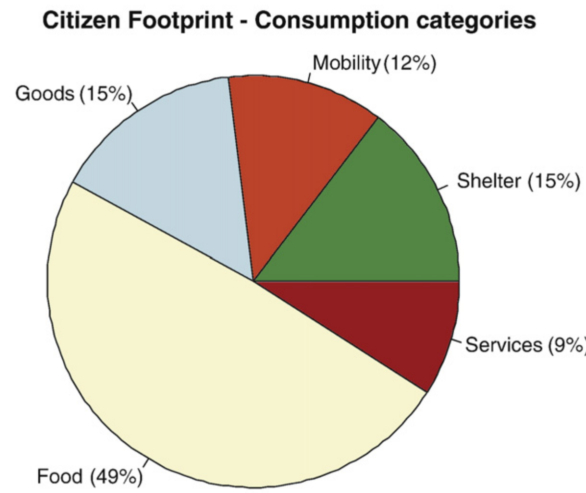

Fig. 3. Citizen Footprint — consumption categories.

Table 3 describes, in detail, how Citizen Ecological Footprint results apportioned to the various consumption items and the land types.

3.2. Territorial Footprint

Impacts of local activities, transportation and services, yield a TF equal to 641 408 gha. Energy land, accounting for 613 804 gha, is the more represented area type, 96% of the final outcome, as shown in Fig. 4.

Fig. 5 summarizes the contributions to TF by the 4 categories.

Energy consumptions by productive processes and traffic show the greatest share of TF. In particular, 409 983 gha are required by fuel consumption (excluding transportation use), which accounts for 64% of TF. Fuel consumption by transportation contributes with 125 057 gha (20% of Territorial Footprint). Electricity consumption requires 59 698 gha of forested land (9% of Territorial Footprint).

Table 4 shows, in detail, the Territorial Footprint outcomes.

3.3. Ecological deficit

The comparison between Ecological Footprint and Biological Capacity requires this latter to be expressed as global Biocapacity. This is recommended because most of the huge industrial cities lack

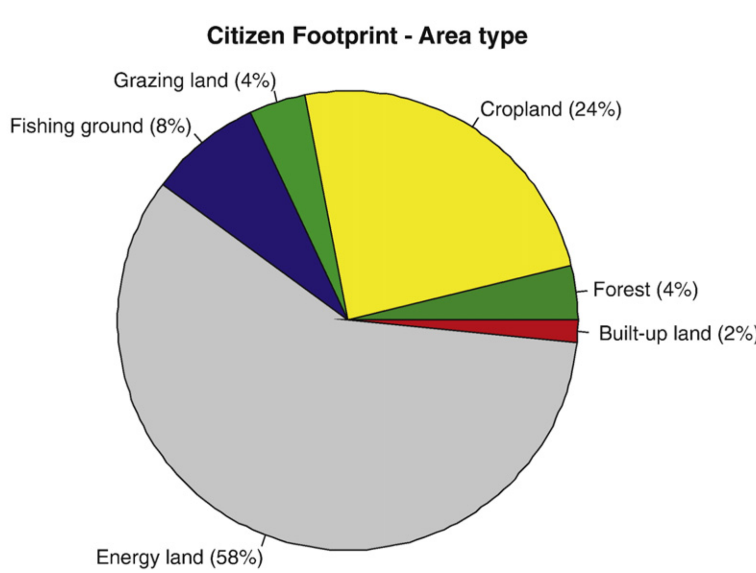

Fig. 2. Citizen Footprint — area type.

Table 3
Piacenza municipality Citizen Footprint (consumptions are defined as per-capita patterns)

	Consumption	CO_2 area ($gm^2\ cap^{-1}$)	Cropland ($gm^2\ cap^{-1}$)	Grazing ($gm^2\ cap^{-1}$)	Fishing ground ($gm^2\ cap^{-1}$)	Forest ($gm^2\ cap^{-1}$)	Built-up ($gm^2\ cap^{-1}$)	Total ($gm^2\ cap^{-1}$)
Food								
Bread and cereals	133 kg	611	1216					1827
Bread, bread sticks and crackers	40 kg	205	369					
Biscuits	14 kg	69	124					
Pasta and rice	63 kg	256	577					
Cakes	9 kg	44	80					
Other	7 kg	37	66					
Meat	70 kg	1478	2571	718				4 767
Beef	20 kg	535	1216	718				
Pork	10 kg	202	306					
Chicken, turkey and rabbit	19 kg	312	400					
Sausages	14 kg	291	439					
Other	7 kg	139	210					
Fish	23 kg	688			3024			3 712
Milk, cheese and eggs	123 kg	501	900	399				1 800
Milk	83 kg	170	213	114				
Cheese	20 kg	257	496	267				
Eggs	7 kg	35	158					
Other	13 kg	39	33	18				
Oils and fats	24 kg	241	1550	19				1810
Olive oil	12 kg	97	808					
Other oils and fats	12 kg	144	742	19				
Potatoes, fruits and vegetables	355 kg	899	615					1514
Fruits	175 kg	532	302					
Potatoes and vegetables	181 kg	367	313					
Sugar, coffee and spices	50 kg	433	1183	84				1700
Sugar	16 kg	49	60					
Coffee, tea and cacao	19 kg	287	831					
Ice creams	12 kg	50	157	84				
Other	3 kg	47	135					
Beverages	462 kg	1 060	370					1 430
Wine	30 kg	182	124					
Beer and other	14 kg	29	31					
Sparkling water	366 kg	743						
Other beverages	52 kg	106	215					
Shelter								
Electricity	1190 kWh	1756						1756
Heating		3601						3601
Methane	640 m^3	3480						
Heating oil	17 l	121						
Built-up area	59 m^2					188		188
Mobility								
Fuels (public & private)		4479						4 479
Methane	25 m^3	136						
Propane	47 l	223						
Petrol	429 l	2738						
Diesel fuel (public & private)	192 l	1382						
Built-up area	59 m^2					195		195
Goods								
Tobacco		31	16					47
Clothes and shoes		67	599	278				944
Furnitures		215				761		976
Household appliance		100						100
Detersives and detergents		547						547
Linen and kitchenware		107	89					196
Medicines		14						14
Means of transportations		984						984
Books and newspaper		805				704		1 509
PC, TV, radio and Hi-Fi		93						93
Others (toys, bags, cosmetics, etc.)		281	24	14				319
Services								
Electricity	1411 kWh	2081						2081
Heating		1130						1130
Methane	196 m^3	1064						
Heating oil	14 l	100						
Built-up area	58 m^2						190	190
Total		22 202	9133	1512	3024	1465	573	37 943

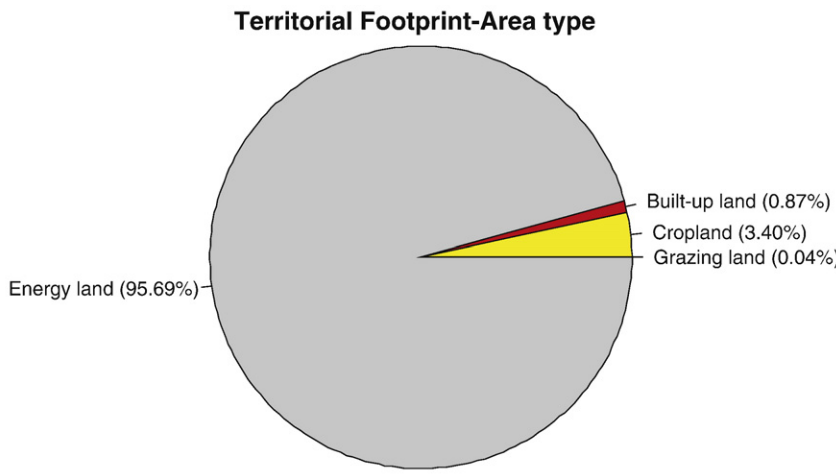

Fig. 4. Territorial Footprint — area type.

substantial local production to support part of their demand of ecological services (Global Footprint Network, 2005a) and they must rely on imported ecological capacity (Barrett and Simmons, 2003; Lewan and Simmons, 2001). Recent assessments give a global average biological capacity of 1.8 global hectares per individual (Wackernagel et al., 2005). We subtracted to this amount the citizen EF and obtained a Global Ecological Deficit (henceforth GED) for Piacenza, which is about 2 gha cap^{-1} (5).

$$\text{GED(gha)}=1.800\ \text{gha cap}^{-1}-3.794\ \text{gha cap}^{-1}=-1.944\ \text{gha cap}^{-1} \quad (5)$$

This value tells us that people living in Piacenza use an area that is twice the biological capacity that, on average, each of them has at its disposal (3.794 gha cap^{-1}/1.800 gha cap^{-1} ≅ 2.1). The fraction that must remain available for biodiversity (12%, as suggested by WCED, 1987) is subtracted from Biocapacity to have a more proper estimate of the Global Ecological Deficit. Accordingly, the new value of GED becomes, approximately, −2.2 gha cap^{-1}.

The same calculation performed using the local Biocapacity holds an intuitive and educational value as it allows citizens to perceive how their requirements exceed the natural capital at their direct disposal (Lewan and Simmons, 2001). Using Italian yield and productivity factors, the Biocapacity available for the Piacenza municipal territory reduces to 33 956 gha, that is 0.400 gha cap^{-1}. This yields a much higher value for the Local Ecological Deficit (henceforth LED), which is equal to −3.394 gha cap^{-1} (6).

$$\text{LED(gha)}=0.400\ \text{gha cap}^{-1}-3.794\ \text{gha cap}^{-1}=-3.394\ \text{gha cap}^{-1} \quad (6)$$

Data and results are summarized in Table 5.

Finally, one can conclude that people living in Piacenza uses an area that is more than 9 times (3.794 gha cap^{-1}/0.4 gha cap^{-1} ≅ 9.5) the biological capacity of its territory. Accounting for 12% of it for biodiversity preservation, Biocapacity lowers to 0.352 gha cap^{-1} and the above ratio increases up to 10.7.

Something similar to ED, that recalls the Ecological Overshoot (EO) (Monfreda et al., 2004), can be calculated using the Territorial Footprint. As this latter cannot be expressed as per-capita value, the EO can be obtained only by subtracting Territorial Footprint from the local Biological Capacity. The calculation yielded 611 527 gha (7). In other words, the Piacenza municipality needs more than 21 times its productive land to sustain economic activities and services (641 408 gha/29 881 gha ≅ 21).

$$\text{EO(gha)}=29\,881\ \text{gha}-641\,408\ \text{gha}=-611\,527\ \text{gha} \quad (7)$$

4. Discussion

In this paper we present, while we discuss a case study, an approach to the Ecological Footprint that distinguishes between the

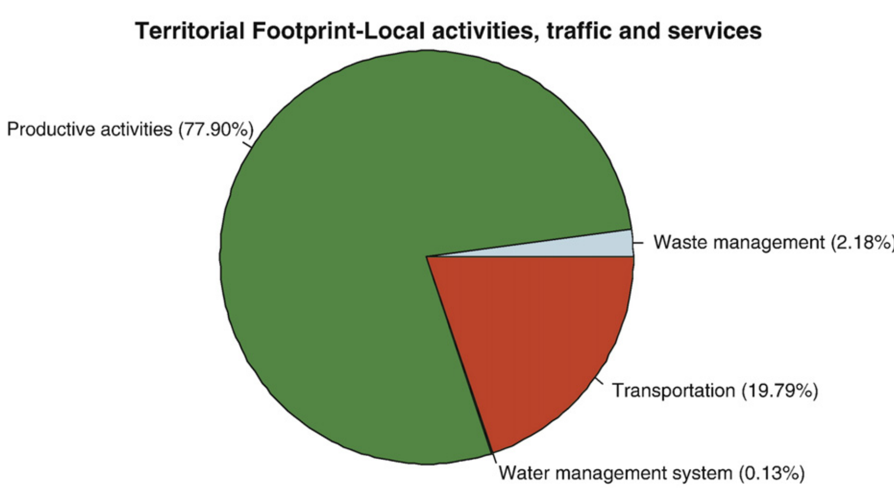

Fig. 5. Territorial Footprint — local activities.

Table 4
Piacenza municipality Territorial Footprint

	Consumption	CO_2 area (gha)	Cropland (gha)	Grazing (gha)	Fishing ground (gha)	Forest (gha)	Built-up (gha)	Total (gha)
Productive activities								
Industry								
Electricity	214 956 103 kWh	31 713						31 713
Fossil fuels		399 503						399 503
Methane	398 467 209 m^3	204 030						
Diesel fuel	1 711 334 l	1162						
Crude oil	286 072 265 l	194 310						
Built-up area	580 ha						1915	1915
Agriculture								
Electricity	2533 372 kWh	374						374
Cropland	6603 ha	4169	21 790					25 959
Pasture	106 ha	63		217				280
Tertiary								
Electricity	187 144 344 kWh	27 611						27 611
Fossil Fuels		10 480						10 480
Methane	18 703 430 m^3	9577						
Heating oil	1 329 341 l	903						
Built-up area	551 ha						1817	1817
Transportation								
Citizen private traffic		29 625						29 625
Methane	2 396 238 m^3	1302						
Propane	4 515 372 l	2126						
Petrol	41 029 753 l	26 170						
Diesel fuel	15 544 034 l	11 208						
Citizen Public Traffic		2001						2001
Diesel fuel	2 775 873 l	2001						
Industrial and tertiary traffic		91 474						91 474
Methane	39 281 m^3	21						
Propane	78 768 l	37						
Petrol	476 159 l	304						
Diesel fuel	126 363 314 l	91 112						
Agricultural fuel		1957						1957
Petrol	59 561 l	2						
Diesel fuel	45 537 774 l	1955						
Roads and facilities	564.4 ha						1863	1863
Waste management								
Special Wastes		12 851						12 851
Not dangerous	80 955 t	11 944						
Dangerous	6151 t	907						
Household wastes	64 887 t	599						599
Truck diesel fuel		558						558
Built-up area	0.6 ha						2	2
Water management system								
Sewerage system		23						23
Purification water plant		305						305
Aqueduct		498						498
Total		613 804	21 790	217			5597	641 408

"geographical" and the "responsibility" criteria. This distinction makes the index more suitable for local policy analysis and development because it allows a systematic assessment of the impacts that are caused by individuals and those due to productive activities and services. This distinction contributes to make clear the relationship between the impacts produced by a human community and the role that is assigned to local authorities as for remedial action through policy making. Something similar to what we call Territorial Footprint has been introduced in the literature on EF. In some applications the EF of productions is confined to single or groups of projects in support of Environmental Impact Assessment (EIA) (Knaus et al., 2006); in some others EF is evaluated for entire production districts (De Leo et al., 2001). In these cases the Territorial Footprint seems to serve more the purpose of optimizing production processes or projects with respect to economic objectives or authorization procedures, such as EIA, than providing a complete picture of the impacts exerted by local communities, which would be required by planning and policy making.

Some other studies considered the impact of productive activities at the nation rather than local level and focused only on certain item such as energy (Medved, 2006). An overall appraisal of impacts through EF was developed for Wales (Barrett et al., 2005) and large municipalities in UK (Barrett and Scott, 2001; Barrett and Simmons, 2003), and in these analysis the EF is used to evaluate also policy scenarios but mostly concerned with the household environment. On the other hand, in Italy the whole bunch of the case

Table 5
Piacenza municipality: biological capacity

Land category	Area (ha)	Equivalence factor (gha ha^{-1})	Productivity factor (–)	Biological capacity (gha)
Forest	3378	1.4	1.3	6148
Cropland	6603	2.2	1.5	21 790
Grazing land	106	0.5	4.1	217
Fishing ground	0	0.4	0.8	0
Built-up land	1 758	2.2	1.5	5801
Total				33 956

Since Biocapacity does not distinguish between CO_2 area and forest, these categories have been aggregated into the latter.

Table 6
Citizen Footprint scenarios according to different carbon absorption rates

	CO_2 area (gha)	Cropland (gha)	Grazing (gha)	Fishing (gha)	Forest (gha)	Built-up (gha)	Total (gha)
0.95 tC ha^{-1} year^{-1}	2.220	0.913	0.151	0.302	0.147	0.057	3.794
	58.57%	24.09%	3.99%	7.98%	3.86%	1.51%	
1.81 tC ha^{-1} year^{-1}	1.165	0.913	0.151	0.302	0.147	0.057	2.735
	42.60%	33.38%	5.52%	11.04%	5.38%	2.08%	
1.42 tC ha^{-1} year^{-1}	1.485	0.913	0.151	0.302	0.147	0.057	3.055
	48.61%	29.88%	4.94%	9.89%	4.81%	1.87%	
1.09 tC ha^{-1} year^{-1}	1.935	0.913	0.151	0.302	0.147	0.057	3.505
	55.20%	26.05%	4.31%	8.62%	4.19%	1.63%	
1.00 tC ha^{-1} year^{-1}	2.109	0.913	0.151	0.302	0.147	0.057	3.679
	57.33%	24.81%	4.10%	8.21%	4.00%	1.55%	
6.6 tC ha^{-1} year^{-1}	0.320	0.913	0.151	0.302	0.147	0.057	1.890
	16.91%	48.32%	7.99%	15.98%	7.78%	3.02%	

studies do not take into account the calculation of EF for productive activity so that the study presented here may be a benchmark, both conceptually and methodologically.

Examples of how EF in the form presented here can be used follow. Recent studies showed that simple actions can lead to some 40% reduction of electricity consumptions in the domestic environment[7]. Most of these interventions, however, are out of the reach of the usual command-and-control policies, as they mostly concern people's lifestyle and, as such, can be adopted only on a voluntary basis.

Nonetheless, there are opportunities for local administrations to affect citizens' Footprint. One possibility is the introduction of new rules in the construction sector to improve energy efficiency of buildings (e.g. better insulating materials and more efficient heating systems). In Italy this matter is regulated by municipal policies. By convincing municipalities to take action in this direction[8] the national government aims to reduce by 20–25% thermic household requirements[9] within year 2013. Applied to Piacenza, a 20% reduction of heating consumption would lower the EF by less than 2% (from 37 943 gm^2 cap^{-1} to 37223 gm^2 cap^{-1}). Clearly this is not a significant effect; in comparison with the overall Footprint this value indicates that the objective of 20% reduction in heating consumption certainly is not a very ambitious one.

Significant reduction in the EF may come from structural policies that can be targeted to productive activities. This concept can be illustrated by considering the power plant that is hosted within the municipal area of Piacenza. This plant uses a mixture of fuels, and consumes 372 737 859 m^3 year^{-1} of methane, 263 722 635 l year^{-1} of crude oil and 202 402 l year^{-1} of diesel oil. These quantities are part of the overall fuel consumption that Table 4 assigns to the industry sector, in the category of productive activities. A Footprint for the sole power plant can be easily calculated: its amount is over 370 123 gha, 85% of the overall industry sector Footprint. What would be the advantage of reconverting the plant to the more efficient combined cycle technology, which makes exclusive use of methane as a fuel? By considering calorific values of methane, crude oil and diesel oil, and the different efficiencies of the two systems (40% for the older technology and 54% for the combined cycle option), we estimated that the same amount of energy presently produced could be obtained burning 506 940 701 m^3 year^{-1} of methane. The increase in methane consumption, however, would produce less carbon dioxide than the mixture of fuels presently adopted. This change would benefit Ecological Footprint for the power plant, as it would be now equal to 259 573 gha per year, 25% less than its present value. Also, the overall Territorial Footprint would be reduced by 17.24%, as well as that of productive activities (−22.13%). Finally, total CO_2 area would be 18.01% less than its present value. These two examples vividly portray the complex situation and the contradictions associated to the use of EF as indicator of sustainability. Clearly, on a local scale policies targeted to productive activities may reduce EF much more than actions taken to modify the consumption patterns of citizens. However, actions promoting a more sustainable lifestyle of individuals may extend the benefits over larger scales. For example, reducing heating consumption may produce a significant reduction of the EF of the whole Italy, although at the single municipality level this contribution seems quite insignificant. On the other side, taking actions to reduce the EF of economic activities may be more difficult because of the reluctance of the stakeholders, mainly for economic and administrative reasons.

When EF of individuals and productions are computed for the same territory (Barrett and Scott, 2001; Barrett and Simmons, 2003) the risk of double counting the impacts generates concern. Double counting may occur because certain impacts are considered both in the Citizen and Territorial Footprints, and combining these two values in a unique index requires particular attention in this respect to avoid overestimation of the overall impact. In the scheme proposed here we do not suggest a strategy to avoid double counting; simply, we state that these two indices must be used separately because they differ from one another conceptually and, as such, they serve different purposes. From these two indices different scenarios as for analysis, remedial actions, and responsibilities emerge. So, if we aggregated the Footprints for Piacenza we should be aware that the energy land required by the power plant would include also the amount needed to compensate for emissions due to quota of electricity produced by the plant and that is consumed by the citizens of Piacenza. Accordingly, an overall Footprint for Piacenza should count this impact only once. However, because the two forms in which the same impact emerge concern different domains of political action, we suggest not to aggregate the indices if they have to be used in support of policy making.

In Italy EF has never been used in support of practical initiatives or local policies. This unexpressed potential is due to several fundamental biases. One of them is certainly the heterogeneity in the methods of calculation. In this scenario things are further complicated

Table 7
Territorial Footprint scenarios according to different carbon absorption rates

	CO_2 area (gha)	Cropland (gha)	Grazing (gha)	Fishing (gha)	Forest (gha)	Built-up (gha)	Total (gha)
0.95 tC ha^{-1} year^{-1}	613 804	21790	217	0	0	5597	641 408
	95.70%	3.40%	0.03%	0%	0%	0.87%	
1.81 tC ha^{-1} year^{-1}	322 162	21790	217	0	0	5597	349 766
	92.11%	6.23%	0.06%	0%	0%	1.60%	
1.42 tC ha^{-1} year^{-1}	410 644	21790	217	0	0	5597	438 248
	93.70%	4.97%	0.05%	0%	0%	1.28%	
1.09 tC ha^{-1} year^{-1}	534 967	21790	217	0	0	5597	562 571
	95.09%	3.87%	0.04%	0%	0%	1.00%	
1.00 tC ha^{-1} year^{-1}	583 114	21790	217	0	0	5597	610 718
	95.47%	3.57%	0.04%	0%	0%	0.92%	
6.6 tC ha^{-1} year^{-1}	88 351	21790	217	0	0	5597	115 955
	76.19%	18.79%	0.19%	0%	0%	4.83%	

[7] For the municipality of Piacenza, in particular, we have that: (a) turning off stand-by of electric devices (e.g. TV, radio and Hi-Fi) would cut electricity consumption by 11%; (b) replacing incandescent with low consumption lamps would further reduce consumption by 8%; (c) substituting traditional household appliances with high efficiency ones would lower it by another 22%. Therefore, adopting all the available best practices for electricity saving, the overall Citizen Footprint could be reduced by 1.92% with respect to the present 37214 gm^2 cap^{-1} used during one year. See the Italian website: www.ambiente.regione.lombardia.it/webqa/dgri/bandofotovoltaico/.

[8] Administrations are often reluctant to impose restrictions that can produce adverse economic effects, such as price increase, with possible negative consequences on the house market. Financial policies based on incentives, however, could be adopted to buffer the negative economic consequences of environmentally oriented policies. One example is a kind of energy certificate called "white certificate", a form of currency that is released to local distributors of energy and that awards their effort to put into practice energy saving initiatives involving the final users, the citizens.

[9] www.ecoblog.it/categoria/risparmio-energetico.

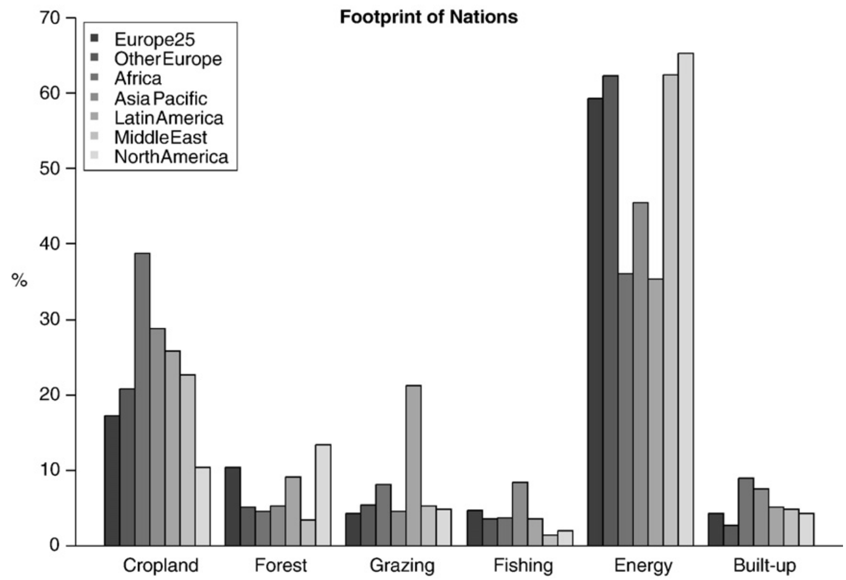

Fig. 6. Ecological Footprint of Nations. In this barplot we summarized and compared the average value of cropland, forest area (forest), grazing land (grazing), fishing ground (fishing), CO_2 area (energy) and built-up land (built-up) for 7 main subgroups of Nations: Europe 25 (25 nations of Europe Union and Switzerland), Other Europe (with European countries not included in the previous database), Africa, Asia Pacific (with countries of West-Asia and Oceania), Latin America (with south and Central American countries, including Caribbean ones), Middle East (with middle east and central Asia countries) and North America (Canada and U.S.A.). Data were obtained from Global Footprint Network (2005b) and written in Table 8.

because coefficients that transform consumptions into land requirements are not re-adjusted to take into account conditions and standards typical of the local reality. For example, in many cases conversion factors to estimate energy land for shelter are taken from household spreadsheet (Wackernagel et al., 2003) as it is (e.g. life cycle embodied energy of a standard Canadian house), although it is clear that the energy efficiency and building materials in Italy are very different from that of Canadian houses. Also, coefficients may vary according to the progress of the knowledge about a certain phenomenon, and spreadsheets should be updated accordingly. If this updating process does not take place, calculations may be affected

Table 8
National Ecological Footprint, 2005 edition (with results through 2002)

	Cropland	Forest	Grazing	Fishing	CO_2 area	Built-up
	(gha)	(gha)	(gha)	(gha)	(gha)	(gha)
Europe 25	0.81	0.49	0.20	**0.22**	2.8	0.2
Other Europe	0.77	0.19	0.20	0.13	2.3	*0.1*
Africa	0.43	*0.05*	0.09	0.04	*0.4*	*0.1*
Asia Pacific	*0.38*	0.07	*0.06*	0.11	0.6	*0.1*
Latin America	0.51	0.18	0.42	0.07	0.7	*0.1*
Middle East	0.47	0.07	0.11	*0.03*	1.3	*0.1*
North America	**0.98**	**1.27**	**0.45**	0.19	**6.2**	**0.4**
Minimum	0.38	0.05	0.06	0.03	0.4	0.10
Median	0.51	0.18	0.20	0.11	1.3	0.10
Mean	0.62	0.33	0.22	0.11	2.0	0.16
Maximum	0.98	1.27	0.45	0.22	6.2	0.40
SD	0.23	0.44	0.16	0.07	2.04	0.11
CV	36.96	132.95	71.93	64.49	100.04	72.16
	Cropland	Forest	Grazing	Fishing	CO_2 area	Built-up
	%	%	%	%	%	%
Europe 25	17.16	10.38	*4.24*	4.66	59.32	4.23
Other Europe	20.86	5.14	5.42	3.52	62.33	*2.71*
Africa	**38.74**	4.50	8.10	3.60	36.03	**9.00**
Asia Pacific	28.78	5.30	**4.54**	**8.33**	45.45	7.57
Latin America	25.75	9.09	**21.21**	3.53	*35.35*	5.05
Middle East	22.59	*3.37*	5.28	*1.44*	62.50	4.80
North America	*10.33*	**13.39**	4.74	2.00	**65.33**	4.21
Minimum	10.33	3.37	4.24	1.44	35.35	2.71
Median	22.60	5.30	5.28	3.53	59.32	4.80
Mean	23.46	7.31	7.65	3.87	52.33	5.37
Maximum	38.74	13.39	21.21	8.33	65.33	9.00

For each area type, the maximum (in bold) and minimum (in italic) are highlighted.

Table 9
Local Ecological Footprints

	Cropland	Forest	Grazing	Fishing	CO_2 area	Built-up
	%	%	%	%	%	%
Legnago	8.44	7.89	17.43	24.41	40.87	0.93
Isernia	9.49	7.76	18.89	**30.71**	32.60	*0.53*
Orvieto	8.94	8.05	19.89	23.63	38.89	0.57
Santiago	12.50	**29.16**	20.83	8.33	*25.00*	4.16
L'Aquila	30.42	6.61	12.96	4.76	42.32	2.91
Pescara	20.26	4.90	8.49	3.26	61.27	1.79
Chieti	29.77	6.87	12.46	4.83	42.74	3.30
Teramo	**32.00**	6.40	13.33	5.06	40.80	2.40
Oslo	11.69	11.00	13.02	8.98	52.54	2.73
Toronto	18.42	17.10	10.52	5.26	46.05	2.63
Santa Monica	18.07	9.69	2.37	3.03	66.22	0.60
Tudela	16.12	11.21	6.90	28.16	35.95	1.62
York	*7.00*	13.00	7.00	0.50	**70.00**	2.50
Torino(C)	29.00	10.00	13.00	3.00	44.00	1.00
London	11.70	6.60	5.50	9.00	65.00	2.20
Victoria	14.00	9.00	10.00	6.00	58.00	2.00
Vienna	14.30	6.00	21.40	1.80	55.60	0.90
Sonoma	11.71	16.21	3.60	3.15	62.61	2.70
Marin	9.85	17.15	2.91	2.55	66.05	1.45
Sarasota	17.00	13.58	*2.24*	2.83	59.19	5.12
S.Francisco	18.08	11.77	2.39	3.01	62.44	2.29
Gansu	29.91	*0.95*	**24.74**	*0.22*	43.52	0.64
Abruzzo	31.31	6.84	13.15	5.00	40.00	3.68
Torino(P)	26.00	11.00	14.00	3.00	43.00	3.00
Catanzaro	23.00	8.00	9.00	1.00	57.00	2.00
Bologna	24.30	7.70	6.30	0.60	56.80	4.30
Rimini	13.00	4.00	21.00	3.00	51.00	8.00
Malmoe	16.60	22.20	12.50	3.00	36.00	9.70
Liguria	28.00	6.00	18.00	5.00	40.00	3.00
Toscana	21.30	8.30	4.50	1.90	57.50	6.50
Piacenza (C)	**24.09**	**3.86**	**3.99**	**7.98**	**58.57**	**1.51**
Minimum	7.00	0.95	2.24	0.22	25.00	0.53
Median	17.54	8.17	12.48	3.21	48.53	2.45
Mean	18.74	10.16	11.61	6.83	49.77	2.84
Maximum	32.00	29.16	24.74	30.71	70.00	9.70

For each area type, the maximum (in bold) and minimum (in italic) are highlighted. C and P in the table stand, respectively, for city and province.

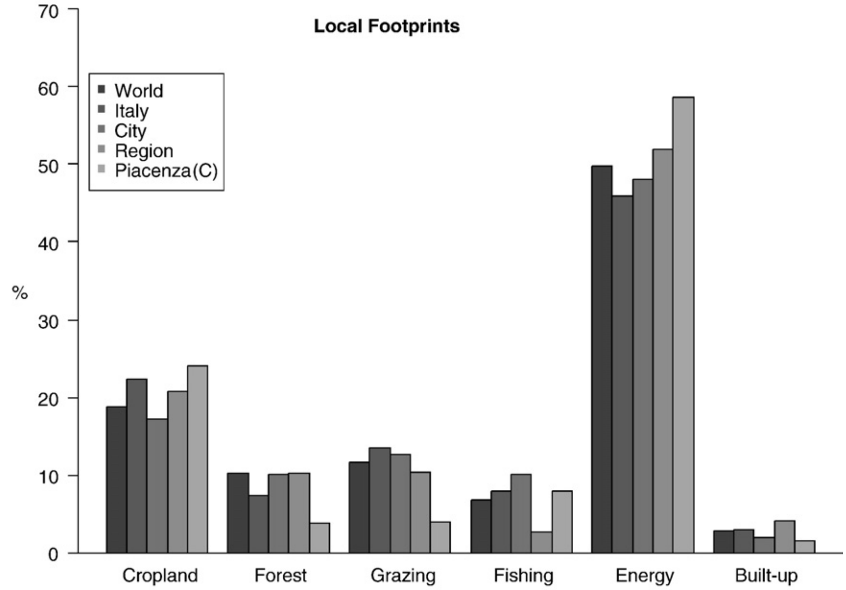

Fig. 7. Local Ecological Footprints. Within this second barplot we analyzed differences in Footprint area types (cropland, forest area, grazing land, fishing ground, CO_2 area — defined as energy — and built-up land) for subgroups of local case studies: World (30 Footprints in the world, both cities and regions), Italy (15 Italian case studies, both municipalities and regions), City (17 cities in the world), Prov (13 regions, counties or provinces in the world) and Piacenza (Citizen Footprint of the municipality as estimated in the text). We divided Local Footprint data as follows: cities (Legnago, Isernia, Orvieto, Santiago, L'Aquila, Pescara, Chieti, Teramo, Oslo, Toronto, Santa Monica, Tudela, York, Torino(C), London, Victoria and Vienna), provinces or counties (Sonoma, Marin, Sarasota, San Francisco, Torino (P), Catanzaro, Bologna, Rimini and Malmoe) and regions (Gansu, Abruzzo, Liguria and Toscana).

by severe drawbacks. Typical is the case of coefficients to assess energy land requirements. In the case of Piacenza we showed how EF changed using the several values assigned to this coefficient in the course of time (see Appendix B). We considered six different conversion factors to calculate both Citizen Footprint and Territorial Footprint of Piacenza[10]. Outcomes, summarized in Tables 6 and 7, show how Citizen Footprint is reduced by more than a half using the highest conversion factor, whereas for the Territorial Footprint this decrease is about six times the value obtained with the lowest coefficient.

To aptly use the EF one must be aware of its intrinsic limitations. It is well known, for example, that Footprint does not consider issues such as chemical pollution. These impacts in fact cannot be measured immediately as consumption of natural capital. In this case, an approach similar to that used by Poor et al. (2007) and that makes use of an economic evaluation of environmental quality could be applied. Other inconsistencies are connected to water consumption and its inclusion within EF calculation (Jenerette et al., 2006a,b; McManus and Haughton, 2006; Monfreda et al., 2004). In addition, there are conceptual difficulties associated to the meaning of the index. Generally, one thinks that the lower the EF the more sustainable is the community. This does not hold in any case. Consider these two scenarios: (a) a steelworks, located within municipal boundaries and forced, by the local administration, to have filter for dusts and a water purification system; (b) a municipality without severe rules to preserve air and water, which hosts a steelworks identical to the previous, that does not adopt any mitigation technology and has an inefficient water depuration system. It is easy to argue that EF in the first scenario would be larger than in the second because electricity consumptions, required by dust abatement system and water purification procedure, increase CO_2 emissions. Paradoxically as it is, end of pipe technologies conceived to improve environmental conditions appear less sustainable. Therefore, the simple value of Ecological Footprint may not tell the entire story about the environmental performance of a settlement or community.

Also, for the practical use of this index, we must say that its impact on decision making process must be weighted in the light of the real political and economic constraints that decision makers face. For example, we have shown that the switching of the local power plant from a blend of three fuels to just the single fuel of methane would reduce the TF by 17.24%. This initiative would impose each citizen a certain cost per year. Suppose that somewhere else in the EF categories (e.g. in the transportation sector) there is another type of conversion (e.g. converting the diesel-fueled public transportation to an alternative fuel) that would reduce the TF by the same 17.24% but at a lower cost. Clearly, this latter option would be preferred. Because sustainability is, at least, a three dimensional concept (i.e. environmental, social and economic), it is clear that the policy force of Ecological Footprint is quite limited whether detached from economic cost–benefit analysis and social evaluations. However, one merit of the index, as calculated according to the method proposed in this paper, is that it allows considering option that would not be using the Citizen Footprint. Certainly, a comprehensive approach must emerge from interdisciplinary ecological evaluation studies in which a measure of sustainability is suitably grounded in both economic and ecological theory.

Appendix A. Energy land in Ecological Footprints

The energy land has the greatest share of EF in the municipality of Piacenza. This is a general evidence we unveiled by browsing a series of case studies from all over the world (average per-capita energy land is 1.20 gha cap^{-1}, equivalent to 53.57% of the whole Footprint). However, the variability around this average is also worth noting. According to *National Ecological Footprint and Biocapacity Accounts 2005 Edition* (*with results throughout 2002*) (Global Footprint Network, 2005b) we pass from the top of 6.2 gha cap^{-1} of North America, to the lowest 0.4 gha cap^{-1} of Africa (see Fig. 6 and Table 8). This picture is well supported by the coefficient of variation for energy land

[10] They are: 0.95 tC ha^{-1} $year^{-1}$ (Wackernagel and Monfreda, 2004), 1.81 tC ha^{-1} $year^{-1}$ (Wackernagel and Rees, 1996), 1.42 tC ha^{-1} $year^{-1}$ (Wackernagel et al., 1999a), 1.09 tC ha^{-1} $year^{-1}$ (Global Footprint Network, 2005b), 1.00 tC ha^{-1} $year^{-1}$ (Global Footprint Network, 2005b) and 6.6 tC ha^{-1} $year^{-1}$ (Valentini et al., 2000). The first five values are based on the average carbon absorption rate of the world forests as estimated by the Redefining Progress and Global Footprint Network, while the last one is the average carbon absorption rate calculated for northern Italy (the area where Piacenza is located), with a different methodology (automated eddy covariance measurements of CO_2 fluxes).

(CV = 100.04%), meaning a wide range of values around the average. The importance of energy land in terms of EF share is shown in Table 8 and Fig. 6.

Considering local Footprints (performed on different sub-national administrative divisions as counties, Italian regions and provinces, municipalities, etc.), Santiago (Chile) shows the smallest percentage value (25%) as for energy land and it is the only local case study, out of the 30 that we examined, where it is not the most important area type (which is forested land for productivity, accounting for 29.17% of EF). York (UK), on the other hand, lies at the opposite extreme with 70% of EF due to energy land. Excluding Santiago (25%), Isernia (Italy, 32.60%), Tudela (Spain, 35.96%), Malmoe (Sweden, 36%) and Orvieto (Italy, 38.90%), all the other Footprints (25/30, about 83%) always show percentage values of energy land larger than 40%. The percentage contributions of the various area type in the 30 local Footprints that we examined are summarized in Table 9. Fig. 7 depicts the average percentage of each area type in 5 subgroups: *World* (which condensate the whole database of 30 local Footprints), *Italy* (15 Italian Footprints), *City* (the Italian and non-Italian 17 municipality), *Prov* (Italian and non-Italian 13 provinces, excluding municipalities) and *Piacenza* (*C*) (showing the area type values of Citizen Footprint calculated in the results; see Table 3). In all the cases energy land remains the most representative part of the Footprint both in Italy and in other developed countries, and the same figure is maintained in sub-national applications. For Piacenza, land required to sustain the energy use by citizens accounts for 58.57% of the overall Footprint. It is larger than the average energy land percentage for the whole world (49.77%), Italy (45.92%), City (48.11%) and Province (51.93%). Nevertheless, the value we calculated for Piacenza is not the highest: Pescara (Italy, 61.28%), Santa Monica (USA, 66.22%), York (UK, 70%), London (UK, 65%), Sonoma (62.61%), Marin (66.06%), Sarasota (59.20%) and San Francisco (USA, 62.44%) show larger share of EF by the energy land.

Appendix B. CO_2 sequestration rate of the world's forest

Energy land is calculated as the biologically productive area needed to sequester CO_2. Average CO_2 sequestration rate of the world forests (SR) and amount of CO_2 emissions are basic values requested to compute energy land. Currently, it is assumed that about 1.8 Giga tonnes of carbon emissions are absorbed by oceans every year (IPPC, 2001), and the rest by world forests (about 73%). CO_2 sequestration rate of the world forests is calculated from FAO's Global Fibre Supply Model (FAO, 2000) and it is equal to 1.09 tC ha^{-1} year^{-1} (8). Since Ecological Footprint has been introduced, values for this coefficient changed. First it was estimated to be 1.81 tC ha^{-1} year^{-1} (Wackernagel and Rees, 1996), then it lowered to 1.42 tC ha^{-1} year^{-1} (Wackernagel et al., 1999a), and further decreased to 0.95 tC ha^{-1} year^{-1} (Wackernagel and Monfreda, 2004). The commonly accepted value is 1.09 tC ha^{-1} year^{-1} (Global Footprint Network, 2005b). Its calculation is as follows

$$\mathrm{SR} = \frac{1.84\ \mathrm{m}^3}{\mathrm{ha\ year}} \cdot \frac{0.5\ \mathrm{t_{dm}}}{\mathrm{m}^3} \cdot 1.9 \cdot 1.25 \cdot \frac{0.5\ \mathrm{tC}}{\mathrm{t_{dm}}} = \frac{1.09\ \mathrm{tC}}{\mathrm{ha\ year}} \tag{8}$$

where 1.84 m^3 ha^{-1} year^{-1} is the world average forest growth rate as defined by FAO; 0.5 t_{dm} m^{-3} (with t_{dm} = tonnes of dry matter) is the average roundwood density for dry weight (IPPC, 1997a); 1.9 is the expansion ratio for logged forests and it accounts for the non-commercial biomass as limbs or small trees (IPPC, 1997b); 1.25 is the factor considering an increase of the CO_2 absorption rate by 25% because roots are not included into starting dry biomass calculus (IPPC, 1997b) and 0.5 tC t_{dm}^{-1} are the tonnes of carbon in 1 tonne of dry matter (t_{dm}).

There are also reports in which CO_2 sequestration rate is calculated considering local forest growing in the study area.

Carbon emission factors and their Footprints

IPPC (1997a) provides carbon emission factors per energy unit obtained from coal (26 tC TJ^{-1}), oil (20 tC TJ^{-1}) and natural gas (15.3 tC TJ^{-1}). It follows that energy from these resources is responsible for different CO_2 emissions. Then, the same amount of CO_2 absorbed by 1 global hectare (gha) per year is associated to various energy consumption patterns, as a function of the fossil fuel used: 42 GJ gha^{-1} year^{-1} for coal (9), 54 GJ gha^{-1} year^{-1} for oil and 71 GJ gha^{-1} year^{-1} for natural gas.

As an example, the coal energy consumption ($\mathrm{ENG_{Coal}}$) corresponding to CO_2 emissions absorbed by 1 global hectare (gha) per year is:

$$\mathrm{ENG_{Coal}} = \frac{\frac{1.09\ \mathrm{tC}}{\mathrm{ha\ year}}}{\frac{0.026\ \mathrm{tC}}{\mathrm{GJ}} \cdot 0.73 \cdot \frac{1.38\ \mathrm{gha}}{\mathrm{ha}}} = \frac{42\ \mathrm{GJ}}{\mathrm{gha\ year}} \tag{9}$$

where 0.73 represents the percentage absorbed by forests and 1.38 gha ha^{-1} is the equivalence factor of energy land (e.g. forests).

The reciprocal of $\mathrm{ENG_{Coal}}$ gives the Footprint required to absorb CO_2 emissions produced by 1 GJ of energy from coal ($\mathrm{EF_{Coal}}$):

$$\mathrm{EF_{Coal}} = \frac{1}{\frac{42\ \mathrm{GJ}}{\mathrm{gha\ year}}} = \frac{0.024\ \mathrm{gha\ year}}{\mathrm{GJ}} \tag{10}$$

Formerly, these energy Footprints were calculated with different coefficients and formulas. To deal with the above inconsistencies, consider the following values calculated for coal:

$$\mathrm{ENG_{Coal1}} = \frac{\frac{1.42\ \mathrm{tC}}{\mathrm{ha\ year}}}{\frac{0.026\ \mathrm{tC}}{\mathrm{GJ}}} = \frac{55\ \mathrm{GJ}}{\mathrm{ha\ year}} \tag{11}$$

$$\mathrm{EF_{Coal1}} = \frac{1}{\frac{55\ \mathrm{GJ}}{\mathrm{gha\ year}}} = \frac{0.018\ \mathrm{gha\ year}}{\mathrm{GJ}} \tag{12}$$

$$\mathrm{ENG_{Coal2}} = \frac{\frac{0.95\ \mathrm{tC}}{\mathrm{ha\ year}}}{\frac{0.026\ \mathrm{tC}}{\mathrm{GJ}} \cdot 0.65} = \frac{56\ \mathrm{GJ}}{\mathrm{ha\ year}} \tag{13}$$

$$\mathrm{EF_{Coal2}} = \frac{1}{\frac{56\ \mathrm{GJ}}{\mathrm{gha\ year}}} = \frac{0.017\ \mathrm{gha\ year}}{\mathrm{GJ}} \tag{14}$$

where Eq. (11) only uses the ratio between the carbon absorption rate of 1.42 tC ha^{-1} year^{-1} (Wackernagel et al., 1999a) and the coal carbon intensity (0.026 tC GJ^{-1}), while in Eq. (13) the carbon absorption rate of 0.95 tC ha^{-1} year^{-1} (Wackernagel and Monfreda, 2004) is divided by the product of the coal carbon intensity (0.026 tC *t*CGJ^{-1}) with the percentage absorbed by forests (0.65).

It is therefore evident that, although the carbon intensity of coal remains the same, changes in the energy land Footprint (gha) corresponding to 1 GJ are detected, depending on carbon absorption rate and ocean uptake values.

These examples show the need of transparency in respect to calculation procedures and coefficients used.

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