Evaluation of carrying capacity and territorial environmental sustainability

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Abstract

Land use has a great impact on environmental quality, use of resources, state of ecosystems and socio-economic development. Land use can be considered sustainable if the environmental pressures of human activities do not exceed the ecological carrying capacity. A scientific knowledge of the capability of ecosystems to provide resources and absorb waste is a useful and innovative means of supporting territorial planning. This study examines the area of the Province of Bari to estimate the ecosystems' carrying capacity, and compare it with the current environmental pressures exerted by human activities. The adapted methodology identified the environmentally sustainable level for one province.

Introduction

Sustainable development aims to meet the needs of the present generations without compromising the ability of future generations *to meet their own needs* (World Commission of Environment and Development, 1987). The transformation of land use plays an important role in sustainable development since it involves changes in the environment and landscape. In fact, land use has a great impact on environmental quality, use of resources, state of ecosystems and socio-economic development (Steiner *et al*., 2000; Marull *et al*., 2007). The anthropic activities exerting pressures on the environment and modifying the status of natural resources, therefore, have an impact on ecosystems and human health. The pressures exerted by human activities on ecosystem structure and function (Scheffer *et al*., 2001) are the production of pollutants (waste, wastewater and gas emissions) and the consumption of renewable and non-renewable resources (Bettini, 1986; Rajaran and Das, 2011). The consumption of natural resources and emission of pollutants modify environmental status and its relationships with chemical, physical landscaping, architectural and agricultural factors. These changes in environmental status caused by human activities in the area, and the implementation of plans, programmes and projects has been termed *environmental impact* by the United Nations Economic Commission for Europe in the Espoo Convention (1991). A deeper knowledge of the relationship between environmental pressures and impact may allow technical interventions and planning of land use to be implemented aimed at achieving sustainable development to be implemented (Dal Sasso, 2001; Holden, 2004).

Land use can be considered sustainable if the environmental pressures of human activities do not exceed the limited capacity of ecosystems to provide resources and absorb waste without compromising their quantity and quality (Graymore *et al*., 2010). In this way, ecosystems ensure the productivity of resources and services essential to future generations (Daily, 1997). In fact, the three conditions set by Daly (1991) to ensure sustainable development are: i) the accrual of the use of renewable resources shall not exceed the related accrued regeneration; ii) the accrual of the use of non-renewable resources shall not exceed the speed of development of renewable substitutes; iii) the emission of pollutants shall not exceed the absorption capacity of the environment.

Methods to assess the environmental sustainability of land use can identify and help implement solutions to protect the ecosystem and minimise the negative environmental impact at the source (Cai *et al*., 2003; Morrissey *et al*., 2006). A method for assessing the sustainability on a regional scale should provide quantitative information about sustainability and the impact of decisions made concerning land use. The most common methods for assessing the sustainability on a regional scale are: i) emergetic analysis; ii) comparing ecological footprint and biocapacity; iii) territorial environmental balance; iv) comparing environmental pressures and carrying capacity.

The methods listed for assessing sustainability are based on the use of indicators highlighting the economic, social and environmental aspects (Castoldi and Bechini, 2010), and to effectively describe the pressures exerted by human activities on natural resources and the impact on ecosystems (Dale and Beyeler, 2001; Niemi and McDonald, 2004). The indicators are, in fact, analytical and interpretative tools of ecological dynamics (Wiggering and Muller, 2004) that can represent any level of complexity (Turnhout *et al*., 2007), therefore providing a useful guide for the implementation of more advanced criteria for land use planning (Colantonio and Galli, 2006). Indicators can be compared with regulatory limit values, objectives (Van Cauwenbergh *et al*., 2007), sustainability thresholds and intervals (Wiek and Binder, 2005; Zahm *et al*., 2006).

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Emergy analysis is based on the use a set of thermodynamic indicators of sustainability expressed in terms of equivalent solar energy (solar emjoule) that make scientific assessments of the interaction between natural and productive economic systems (Franzese *et al*., 2003). Emergy (Odum, 1996) is a thermodynamic quantity that represents the work done by the environment to generate ecosystem services that living systems must use optimising the outputs (Ulgiani *et al*., 1994).

The ecological footprint is an aggregate and synthetic indicator developed by Wackernagel and Rees (1996) that represents the ecologically productive area needed to produce the resources consumed and to absorb the waste generated by humans (Monfreda *et al*., 2004). The area can effectively represent and communicate the finiteness of the planet Earth and its ability to generate resources (Wackernagel and Rees, 1997). The comparison between the ecological footprint and the effective presence of ecologically productive land (biocapacity) identifies the ecological deficit or surplus of a local context. Currently, the Italian biocapacity is able to meet only 34.8% of the ecological footprint leaving an ecological deficit amounting to 65.2% (Tiezzi and Marchetti, 2003). The ecological footprint recognises the role of natural capital but does not take into account the regenerative capacity of the resources. To overcome this limitation, the concept of a three-dimensional ecological footprint has been recently introduced. It estimates the time required for regeneration of the natural resources consumed annually (Niccolucci *et al*., 2009).

The territorial environmental balance is a dynamic spatial analytical tool developed by the Technical Research Centre of Finland in the 1990s (Harmaajarvi, 2000) that evaluates the effects of land use on environmental equilibrium through the use of indicators (Maffiotti *et al*., 2008).

The comparison between environmental pressures from human activities produced at defined sites and the environmental carrying capacity is the most important and significant procedure to assess sustainability on a regional scale (Yin *et al*., 2010). The carrying capacity is a concept rooted in demography as applied to ecology and biology (Clarke, 2002), and was introduced by Odum (1988) as *the number of individuals that can be sustained indefinitely in a given habitat without causing damage to the productivity of ecosystem on which their livelihoods depend*. This concept has been extended to the environmental sector and it has been defined as the maximum consumption of natural resources and waste discharge that can be supported in an area without compromising the ecosystem status (Khanna *et al*., 1999; Oh *et al*., 2005).

Numerous attempts to quantify the exact carrying capacity have been conducted but there are still no effective and efficient methods (Graymore *et al*., 2010; Lane, 2010) because of practical problems associated with its measurement (Papageorgiou and Brotherton, 1999) and the complexity of ecosystem dynamics (Holling *et al*., 2000). Most of the existing methodologies for determining the environmental carrying capacity of a territory are based on estimated flows of resources (water, energy, land) and waste (emissions, solid waste, wastewater) that affect the environmental status (Wackernagel and Rees, 1996; Tang and Ye, 1998; Khanna *et al*., 1999; Yu and Mao, 2002; Clarke, 2002; Komatsu *et al*., 2005; Oh *et al*., 2005; Graymore *et al*., 2010; Yin *et al*., 2010; Liu and Borthwick, 2011). These flows are defined as *critical flows or sustainability thresholds* and can be estimated through complex operations based on policy environmental standards and the capacity of ecosystems to provide resources and assimilate the wastes (Kang and Xu, 2010; Dal Sasso, 2001). The determination of the total carrying capacity cannot be expressed only through the individual sustainability thresholds, but must also take into account the connections between them (Komatsu *et al*., 2005; Yin *et al*., 2010).

The comparison between the environmental pressures exerted by human activities and their sustainability thresholds can be made using indicators to assess current environmental sustainability or that expected in the future by land use planning (Graymore *et al.*, 2010; Dal Sasso, 2001). The results of the comparison between pressure and environmental sustainability thresholds based on carrying capacity can, therefore, give useful information for planning, environmental management and the Strategic Environmental Assessment (SEA) (Godschalk and Parker, 1975; Baldwin, 1985; Ng and Obbard, 2004).

The objective of this study is to assess the environmental sustainability on a regional scale by comparing the environmental pressures and the estimated carrying capacity in the study area (Province of Bari). An understanding of the environmental sustainability levels on a regional scale is the first step towards land use planning that protects the environment.

Materials and methods

In the present study, consumption of resources, production of emissions, environmental quality standards and the capacity of ecosystems to provide resources and absorb the emissions were evaluated in an area of study. The study area coincided with the Province of Bari (Figure 1) located in Southern Italy. The province covers 5138.20 km^2 (513,820 ha) and has a resident population of approximately 1,590,000.

The environmental pressures and environmental carrying capacity of the Province of Bari were assessed.

Evaluation of environmental pressures

In the first phase, environmental pressures (resource flows, air emissions, water discharges and waste) were analysed and quantified through consultation of technical documents (Puglia Region, 2009; ARPA Puglia, 2009; ARPA Puglia, 2010) and databases (ISPRA, 2005). The data relating to consumption and emissions in the study area were processed using an appropriate set of environmental indicators (Table 1). These indicators are those most commonly used in the technical and scientific literature (Graymore *et al*., 2010; ARPA Puglia, 2010; Liu and Borthwick, 2011) and legislation (European Commission, 2009) because they represent the ecological dynamics and describe environmental problems.

The water consumed in the Province of Bari comes from aquifers (42.2%), provincial and extra-provincial surface waters (29.6%) and extra-provincial sources (28.2%) (Puglia Region, 2009). The external provincial water supply is ensured by a complex aqueduct system built at the beginning of the twentieth century (Acquedotto Pugliese). Water consumption covers drinking water (61.6%), agricultural use (32%) and industry (6.4%) (Puglia Region, 2009).

In the Province of Bari, there are several energy production plants powered by fossil and renewable sources that produce a surplus over demand. The electricity consumed by these activities (agriculture, industry, residential, tertiary) in the Province of Bari is approximately 4600 GWh (ARPA Puglia, 2010).

The area occupied by urban, industrial and agriculture in the Province of Bari is growing steadily (ARPA Puglia, 2009). The consumption of land, although often reversible, causes the degradation of soil that is removed from its natural function (European Commission, 2006). The land area given over to agricultural activities, residential areas, industrial sites and *quarries* in the Province of Bari is approximately 431,678 ha (ARPA Puglia, 2009), *i.e.* 84% of the total area.

The Province of Bari is also characterised by the presence of numerous protected areas which interest an area of approximately 138,724 ha, *i.e.* 27% of the total area (ARPA Puglia, 2010): national parks (Alta Murgia and Gargano), regional parks (Lama Balice, Lakes of Conversano and Gravina Monsignore) and sites of importance to the community (Murgia dei Trulli, Bosco Difesa Grande, etc.). The protected areas of the province of Bari are characterised by the presence of agro-livestock activities that constitute the biggest source of employment for the local population.

Fertilisers are used in rural areas (mineral fertilisers, organic fertilisers, soil conditioners, correctives) that have a positive impact on the chemical-physical and microbiological characteristics of the soil. However, excessive fertilisation can at the same time cause pollution of groundwater and eutrophication of surface waters. In the Province of Bari, 157,065 tonnes of fertilisers are used (ARPA Puglia, 2009) that, assuming a nitrogen content equal to 5%, means the application on agricultural soil of 7853 tonnes of nitrogen.

Annual emissions in the atmosphere of CO_2, NOx, PM2.5, PM10, benzene, ammonia, dioxins and furans are set out in the National Inventory of Emissions to Atmosphere of the ISPRA (2005). This is the most comprehensive, consistent and transparent source of information on emissions at a regional and a provincial level.

The Province of Bari has 32 wastewater treatment plants with a water discharge flow of 550,800 m^3/day (Puglia Region, 2002) amounting to 201 Mmc/year. The wastewater treatment plants ensure that the physical-chemical and microbiological quality of discharge conforms with that set out in current EU (European Commission, 1991) and national (Italian Regulation, 2006) legislation. The resident population in the Province of Bari produces 831,998 tons/year of municipal solid waste and production activities are the source of 602,315 tons/year of special waste (ARPA Puglia, 2010) with a consequent annual production *pro capita* of 900 kg/year. Differentiated waste collection is 18% of the total municipal solid waste generated (ARPA Puglia, 2010).

Environmental carrying capacity

In the second phase of the study, the environmental carrying capacity of the Province of Bari was evaluated by estimating the critical flow of resources, emissions, water discharge and waste (Table 2). The critical flows have been identified both on the basis of objective data related to resource availability, and scientific and regulatory environmental quality standards.

The critical flows were identified through the methodological procedures described below and are associated with each environmental indicator (Table 3).

Sustainable consumption of resources: water, electricity, soil, fertilisers

Consumption of water resources is sustainable when it does not exceed 60% of average annual water body recharge. This threshold protects the quality status of the water, of the landscape and of the natural features of water bodies (Smakhtin *et al*., 2005). The water bodies of the Province of Bari are the Murge hydrogeological units and the artificial Locone dam that intercepts the waters of the stream of the same name.

The annual recharge of water bodies in the Province of Bari has been calculated on the basis of hydrogeological and hydrological balance and is equal to 1068 Mmc for the Murge aquifer (Lattarulo *et al*., 2001) and 8 Mmc for the Locone dam (Ranieri and Lagrotta, 2003). The flow of water resources is critical and amounts to 645 Mmc/year.

Figure 1. Province of Bari.

Table 1. Environmental indicators used in the sampling area (Province of Bari).

Indicator		Flow (p_i)	Units of measurement	Bibliographic source
1	Annual consumption of water resources	419	Mcm/year	Puglia Region, 2009
2	Annual consumption of electricity *per capita*	2800	kWh inhabitant/year	ARPA Puglia, 2010
3	Utilized land area	431,678	ha	ARPA Puglia, 2009
4	Unprotected land area	375,096	ha	ARPA Puglia, 2010
5	Nitrogen applied annually to agricultural soil	7853	t/year	ARPA Puglia, 2009
6	CO_2 annual emissions	3,390,925	t/year	ISPRA, 2005
7	NOx annual emissions	21,643	t/year	ISPRA, 2005
8	PM2.5 annual emissions	3069	t/year	ISPRA, 2005
9	PM10 annual emissions	3588	t/year	ISPRA, 2005
10	Dioxins and furans annual emissions	4	g-TEQ/year	ISPRA, 2005
11	Benzene annual emissions	280	t/year	ISPRA, 2005
12	Wastewater annual emissions	201	Mmc/year	Puglia Region, 2002
13	Annual production of solid waste *per capita*	900	kg inhabitant/year	ARPA Puglia, 2010
14	Percentage undifferentiated waste collection	82	%	ARPA Puglia, 2010

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Table 2. Critical flow of resources/emissions in sampling area (Province of Bari).

	Indicator	Determination of the critical flow	Critical flow (c_i)	Units of measurement	Bibliographic source
1	Available water resources	Bibliographic target: 60% of annual water bodies recharge	645	Mmc/year	Lattarulo *et al.*, 2001; Smakhtin *et al.*, 2005; Ranieri and Lagrotta, 2003
2	Sustainable energy consumption *per capita*	Bibliographic target	12,000	kWh inhabitant/year	Graymore *et al.*, 2010
3	Maximum modified land area	Bibliographic target: 80% of total land area	411,064	ha	Graymore *et al.*, 2010
4	Maximum unprotected land area	Bibliographic target: 75% of total land area	385,373	ha	Graymore *et al.*, 2010
5	Maximum annual nitrogen supply to agricultural soil	Bibliographic target compared to territorial extension	4510	t/year	BUWAL, 1996
6	CO_2 maximum annual emissions	Legislative target: -20% of 1990 emissions	4,564,857	t/year	European Commission, 2008a
7	NOx maximum annual emissions	Legislative target: -40% of 2000 emissions	15,027	t/year	BUWAL, 2005a
8	PM2.5 maximum annual emissions	Bibliographic target compared to territorial extension	865	t/year	BUWAL, 2005b
9	PM10 maximum annual emissions	Bibliographic target compared to territorial extension	1493	t/year	BUWAL, 2005b
10	Dioxins and furans maximum	Bibliographic target compared to territorial extension annual emissions	4.3	g-TEQ/year	BAG *et al.*, 2003
11	Benzene annual emissions	Bibliographic target compared to territorial extension	65	t/year	BUWAL, 2003
12	Wastewater maximum annual emissions	Bibliographic target: -15% current water discharge	171	Mmc/year	Dal Sasso, 2001
13	Maximum annual production of solid waste *per capita*	Bibliographic target	750	kg inhabitand/year	Graymore *et al.*, 2010
14	Maximum percentage undifferentiated waste collection	Legislative target	35	%	Italian Regulation, 2006

Table 3. Assessment of the environmental sustainability on regional scale in the sampling area (Province of Bari).

	Indicator (N)	Flow (d_i)	Critical flow (c_i)	Units of measurement	p_i	r_j	r_j^2
1	Annual water resources consumption	419	645	Mmc/year	0.35	0.65	0.42
2	Annual electricity *per capita* consumption	2800	12,000	kWh inhabitant/year	0.77	0.23	0.05
3	Land area utilized	431,678	411,064	ha	-0.05	1.05	1.10
4	Unprotected land area	375,096	385,373	ha	0.03	0.97	0.95
5	Nitrogen applied annually to agricultural soil	7853	4510	t/year	-0.74	1.74	3.03
6	CO_2 annual emissions	3,390,925	4,564,857	t/year	0.26	0.74	0.55
7	Nox annual emissions	21,643	15,027	t/year	-0.44	1.44	2.07
8	PM2.5 annual emissions	3069	865	t/year	-2.55	3.55	12.59
9	PM10 annual emissions	3588	1493	t/year	-1.40	2.40	5.78
10	Dioxins and furans annual emissions	4	4.3	g-TEQ/year	0.07	0.93	0.87
11	Benzene annual emissions	280	65	t/year	-3.31	4.31	18.56
12	Wastewater annual emissions	201	171	Mmc/year	-0.18	1.18	1.38
13	Annual production of solid waste *per capita*	900	750	kg inhabitant/year	-0.20	1.20	1.44
14	Percentage of undifferentiated waste collection	82	35	%	-1.34	2.34	5.49
						Total	54.28

The annual *pro capita* energy consumption was defined as being sustainable up to 12,000 kWh/ab year (Graymore *et al*., 2010) making this the critical flow of energy in the study area.

The percentage of land that can be modified by man's agricultural, industrial, residential and service activities must not exceed 80% of the total land area (Graymore *et al*., 2010) in order to protect soil biodiversity and bio-geo-chemical function. The critical flow of land in the Province of Bari is, therefore, 411,064 ha.

Portions of land that are protected for species, habitat conservation and the landscape environment must be over 25% of the total land area (Graymore *et al*., 2010). The land area of the province of Bari is not subject to protection and should, therefore, be up to 385,373 ha. For Switzerland, the maximum amount of nitrogen added to the arable soil by fertilisation and irrigation has been reported to be 17,000 tonnes/year (BUWAL, 1996). Considering the ratio of the operative agricultural area of Switzerland compared with that of the Province of Bari the critical flow of nitrogen in the study area is 4510 tons/year.

Emissions assimilated from the environment: CO_2, NOx, PM10, PM2.5, benzene, dioxins and furans

The capacity of the atmosphere to absorb pollutants without compromising air quality depends heavily on weather conditions, and soil and emissions' characteristics (Goyal and Chalapati Rao, 2007).

The climate and energy legislative package adopted by the European Parliament has imposed a 20% reduction in CO_2 emissions with respect to those of 1990; therefore, the critical flow of CO_2 in the Province of Bari is 4,564,857 tons/year.

The critical flows of NOx, PM10, PM2.5, benzene, dioxins and furans have been proposed by BUWAL (2003, 2005a, 2005b) and BAG (2003) for Switzerland. Given their technical and scientific value, these critical flows have been adopted in this study and compared to the total area of the Province of Bari.

Water discharge that can be assimilated by the environment

The wastewater produced by households and industrial activities are treated in sewage treatment plants before being discharged into the environment. Treatment of wastewater reduces the concentration of pollutants in the water and avoids environmental contamination. The assimilation of wastewater pollutants by the receiving water body depends on the hydrodynamic and biological characteristics of natural waters (Tett *et al*., 2007) and chemical-physical properties of pollutants. The flow of water discharge must, however, be reduced by 15% (Dal Sasso, 2001) to avoid degradation of inland surface waters, coastal waters and groundwater quality. The critical flow of wastewater in the Province of Bari is 171 Mmc.

Production and sustainable waste management

Waste management must be performed according to the principles of precaution, prevention and sustainability (European Commission, 2008b). It is, therefore, necessary to reduce the production of waste, increase separate waste collection and the subsequent recycling, and avoid landfill.

The critical flow of waste *per capita* was set at 750 kg inhabitants/year (Graymore *et al*., 2010) with a minimum rate of separate waste collection of 65% (Italian Regulation, 2006).

Evaluation of the environmental sustainability on a regional scale

In the third phase of the study, we determined the environmental sustainability of current land use in the Province of Bari by comparing environmental pressures (flows of consumption/emissions) and environmental carrying capacity (critical flows of consumption/emission).

The comparison was made using the method developed by Liu and Borthwick (2011) that allows a precise quantitative assessment of territorial sustainability. The method is based on the direct comparison between flows (p_i) and critical flows (c_i) both for each indicator and overall.

The direct comparison between flows and critical flows for each indicator assesses the surplus (+) or deficit (-) of carrying capacity with respect to environmental pressure (d) in relation to each environmental aspect considered (water consumption, energy consumption, etc.) according to the formula:

$$d_i = 1 - \left(\frac{p_i}{c_i} \right)$$

where $d_i>0$ each environmental pressure is lower than carrying capacity while when $d_i<0$ each environmental pressure exceeds the carrying capacity of the study area. The overall comparison between flows and critical flows assesses the surplus (+) or deficit (-) of the total carrying capacity with respect to environmental pressure (D) in the study area according to the formula:

$$D = 1 - \sqrt{\frac{\sum (r_j)^2}{N}}$$

where N is the number of indicators and r_j the relationship between environmental pressures (p_i) and carrying capacity (c_i) for each indicator. When $D>0$, the environmental pressures are lower than the total carrying capacity of the study area and when $D<0$, the environmental pressures are higher than the carrying capacity.

Results and discussion

This study synthesised a numerical value with the overall ratio between environmental pressures and carrying capacity in the study area. In the Province of Bari, the overall deficit of carrying capacity with respect to environmental pressure is -0.97. To reset the modest ecological deficit it is necessary to reduce the overall environmental pressure to the maximum carrying capacity of the territory.

The methodology also evaluated the surplus or deficit of the load carrying capacity according to single environmental pressures. This approach identifies those environmental pressures that exceed the load capacity and helps formulate the technical options and strategies to be adopted in the development of the area necessary to reduce the total environmental load.

An analysis of results showed that the overall deficit of carrying capacity in the study area is mainly related to environmental pressures generated by the high emission of benzene and particulate matter (PM2.5 and PM10) and the low percentage of separate waste collection. The environmental pressures related to energy and water consumption and atmospheric emissions of dioxins and furans are lower than the carrying capacity.

The methodology can, therefore, be used in the context of advanced territorial planning to assess the environmental load generated by local transformation to verify how far maximum environmental carrying capacity will be respected.

Assessment of territorial environmental sustainability using the methodology developed and applied in the study area can support the choices of transformation and land use of the area, providing a significant boost to sustainable development.

Conclusions

This study has allowed us to develop and apply appropriate analytical methodology to estimate the carrying capacity of ecosystems and assess environmental sustainability in the study area. The proposed methodology broadens our understanding of the ecological balance of the area through a comparison of environmental pressures resulting from human activities and the carrying capacity of support ecosystems. Application of this methodology in the Province of Bari allowed an individual and global analysis of the interchange between human activities and ecosystems to identify the environmental pressures that may affect ecosystem stability. The proposed methodology can also be applied to numerically compare the ecological balance of different areas to ensure its environmental sustainability and establish the most appropriate policies for the exchange of resources. The accuracy of the methodology can be increased through the integration of environmental indicators and details with estimates of the capacity of ecosystems to provide resources and absorb the emissions. An understanding of the capacity of ecosystems within a particular area to provide resources and absorb emissions, effluents and waste is a useful guide to modern planning criteria conforming to socio-economic and environmental protection needs. Through evaluation of territorial environmental sustainability based on carrying capacity of ecosystems it is possible to assess in advance the effects of territorial changes on the environmental balance. The proposed methodology, therefore, assesses the current or future sustainability of land use in order to avoid irreversible changes to the balance of ecosystem status and to develop guidelines for environmental and socio-economical sustainable territorial development.

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