Changes in ecosystem services from wetland loss and restoration: An ecosystem assessment of the Danube Delta (1960-2010)

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ABSTRACT: Deltaic flood plains provide critically important ecosystem services, including food production, fresh water, flood control, nutrient cycling, spiritual values and opportunities for recreation. Despite growing recognition of their societal and ecological importance, deltaic flood plains are declining worldwide at alarming rates. Loss of wetland ecosystem services bears socio-environmental costs overlooked in land-use planning. Conversely, wetland restoration can deliver important long-term benefits. This paper examines effects of different land use policies on ecosystem services provided by the Danube Delta, one of Europe's largest and most outstanding wetlands. First, we identify, characterize and measure the most important ecosystem services provided by the Danube Delta. Second, we assess trends between 1960 and 2010, contrasting periods of economic development (1960-1989) and ecological restoration (1990-2010). Our results indicate that i) the Danube Delta provides important services with benefits accrue from local communities to humanity at large, ii) that two thirds of the Delta's ecosystem services have declined over the studied period and iii) that ongoing restoration efforts have so far been unable to reverse trends in ecosystem service decline. Benefits from ecological restoration policies are already becoming apparent, but at a scale not yet comparable to the costs from ecosystem decline incurred over previous decades.

Key words: ecosystem assessment, socio-environmental costs, wetlands, restoration, Danube Delta, Romania.

1. Introduction

Deltaic flood plains provide critically important ecosystem services for human well-being, including food production, freshwater, flood control, nutrient cycling and many immaterial benefits like opportunities for ecotourism and recreation (Gren et al., 1995; MA, 2005; Uhel et al., 2010; Zorilla et al., 2014). Despite growing recognition of their societal and ecological importance, flood plains are being lost or degraded at alarming rates due to infrastructure development, land use change, unsustainable water withdrawal, pollution, and invasive alien species (MA, 2005; Niculescu et al., 2015). A study collecting data from 14 of the 42 world's largest deltas found that 15 845 km^2 of wetlands in deltaic flood pains have been lost in the period 1994-2008, and it is estimated that wetland loss in the world's 42 largest deltas could be of 364 000 km^2 over the following 15 to 20 years (Coleman et al., 2008).

Besides mounting impacts on biodiversity (Gibbs, 2000), wetland loss has accelerated the decline of critically important ecosystem services (MA, 2005; Zorrrilla et al., 2014), causing large socio-environmental costs for society that tend to be overlooked in economic and land use policy (TEEB, 2010). For example, studies suggest that loss of coastal wetlands increases human and property loss from climate extremes (Costanza et al., 2006; Green et al., 2016). Conversely, research suggests that ecological restoration of wetlands and their services can provide multiple social and economic benefits (Rey-Benayas et al., 2009; de Groot et al., 2015; Elmqvist et al., 2015; Pouso et al., 2018, 2019).

Sound decision making for wetland management requires information about the full range of its social, ecological and economic values affected by development projects (MA, 2005; Gómez-Baggethun and Martín-López, 2015). This paper builds on recent contributions to this journal on the assessment and valuation of ecosystem services (Sharma et al., 2015; Jacobs et al., 2016; Kadykalo and Findlay, 2016; Barton et al., 2018; McInnes and Everard, 2017; Dunford et al., 2018; Xu et al., 2018) to advance our understanding of the effects of different land use policies on wetland ecosystem services. To do so, we conduct a case study in the Danube Delta, one of Europe's largest and most emblematic wetlands, declared a Biosphere Reserve in 1990. Our specific objectives are twofold. First, to identify, qualify and (when applicable) quantify the most important services provided by the Danube Delta using appropriate indicators for their accounting and valuation. Second, to conduct a biophysical assessment of the ecosystem service trends from 1960 to 2010, assessing their evolution throughout management periods dominated by economic development and environmental conservation policies, respectively.

2. Study area

Our research was conducted in the Danube Delta Biosphere Reserve (DDBR). The Danube Delta is Europe's second largest delta after the Volga, and Europe's largest continuous marshland. It includes the world's greatest plain of reed beds, providing a unique nesting place for waterfowls. Over 7 700 species have been recorded, including 341 bird species, of which at least 176 breed in the DDBR. The DDBR is habitat for many endangered and endemic species and a major stopover point for birds migrating between Europe, the Middle East, and Africa. The diversity of species it hosts and its location at the intersection of major European bird migration routes, makes it an area of exceptional ecological importance.

2.1. Site description

Before reaching the Black Sea, the Danube River travels 2 860 km from its spring in the Black Forest Mountains (Germany) across ten European countries. The Danube Delta covers a surface of 4 180 km^2 shared between Romania (84%, 3 510 km^2) and Ukraine (16%, 670 km^2), in Eastern Europe (Fig. 1). The Danube's major arms are Sf. Gheorghe to the south (70 km, 1 500 m^3/s), Sulina in the middle (64 km, 1 250 m^3/s), and Chilia to the north (120 km, 3 800 m^3/s). Together with 470 lakes connected by about 3 500 km of channels, these arms sustain a complex pattern of land cover types and ecosystems, including semi-natural wetlands and lagoons, inland marshes and natural grasslands, sand dunes, beaches, broadleaved forests, and large areas converted for aquaculture and agriculture (Bondar, 1990; Gâştescu and Ştiucă, 2008). The Romanian part of the DDBR, to which our study is circumscribed, covers 5 800 km^2 and includes the Danube Delta itself (3 510 km^2), the delta's upstream floodplain (115 km^2), the Razim-Sinoie lake complex (1 145 km^2), and the Black Sea coastal waters up to 20 m depth (1 030 km^2).

[INSERT FIGURE 1 ABOUT HERE]

Fig. 1. Location of the Romanian part of the Danube Delta Biosphere Reserve. Source: Danube Delta National Institute, Tulcea; Source of the data about areas (ha): Gâştescu and Ştiucă 2008.

2.2 Socioeconomic characteristics

The Danube Delta population increased from 12 000 inhabitants in 1900 to almost 20 000 in 1966, before declining down to 12 638 inhabitants by 2011 (Romanian National Institute of Statistics, 2011). Population decline and aging is due to migration of the youth to cities motivated by difficult living conditions, isolation, lack of opportunities for employment, and difficult transport conditions. The region has a poor infrastructure for education and health care (Boja and Popescu, 2000).

Population density is approximately 5 persons/km^2. About one third of the population lives in Sulina town and the rest is distributed in 24 rural settlements. More than 14 nationalities coexist peacefully within the DDBR (Gâştescu and Știucă, 2008). They are preponderantly Romanians (77.4%) followed by Russian Lipovans (16.95%), Ukrainians, (3.52%), and small communities of Greeks (0.74%), Roma (0.81 %), Turks, Tatars and Hungarians. In the last 25 years the population has kept declining at a comparable rate with the rest of the country (European Commission, 2010).

Most people in the Delta live on the exploitation of natural resources. About two thirds of the population live on fishery and agriculture, and more than 40% are officially registered fishermen (Gâştescu and Știucă, 2008). Subsidiary occupations include animal husbandry, cattle grazing, beekeeping and tourism. Fishing is controlled through fisheries which assign quotas and purchase the fish harvest.

2.3. Background

The Danube Delta has a millenary history of human occupation (Giosan et al., 2012) but the pace of human-induced environmental change increased drastically since the mid-19th century through several waves of large-scale interventions that gradually modified the delta's ecosystem structure and function (Romanescu, 1999; Bretcan et al., 2008; Romanescu and Stoleriu, 2014). For the purposes of this research, two periods require particular attention: one dominated by economic development policies (1860-1989) and the other dominated by conservation and restoration policies (1990 to the present).

The development period can be divided in different stages (Bondar, 1990). First large-scale interventions took place between 1858 and 1907 to change one of the Danube's main arms, Sulina, from a fluvial to a maritime navigation way. The Sulina arm was deepened and shortened from 91 to 64 km. Between 1982 and 1992, channelization of the Sf. Gheorghe arm reduced its length from 108 to 65 km (Cioacă, 2002). This channelization increased the volume and speed of the river flow, increasing erosion and producing large-scale disruptions in the sedimentary balance (Giosan et al., 1999; Uhel et al., 2010).

Construction of canals continued during the 20th Century (Giosan et al., 2013). Between 1903 and 1960, transformations were primarily aimed at improving fish production. Existing canals were enlarged, and new ones were built. A new and more intensive campaign of hydro-technical works followed in the 1960s. Dams were built to regulate water levels in order to enhance reed production and facilitate its harvesting and transportation to cellulose factories (De la Cruz, 1978). In the 1970s attention turned back to fish production and extensive areas were diked for enhancing commercial fish production. In the 1980s agriculture became the primary objective as the communist regime aimed at converting 41% of the Delta into Romania's largest agricultural extension (Ebert et al., 2009). Water courses were extensively altered by new polders, mainly in the North-Western part of the Danube Delta (Baboianu and Staraş, 1993).

Human interventions over the 19th and 20th Centuries impaired the Delta's ecological structure and function severely. Ebert et al. (2009) report that wetland reclamation through dyke construction decreased drastically the connectivity between the floodplains and the Danube River. Coleman et al. (2008) report that by 1987, the Danube Deltas wetlands had declined by 62% due to subsidence, changes in channel geometry, and other anthropogenic interventions. Uhel et al. (2010) report that by the early 1990s, dammed areas covered 977 km^2 and that many ecosystem services had been lost or severely damaged.

Political changes following the fall of the communist regime in 1989 gave way to a new era of management policies, during which conservation of natural values and recovery of wetlands functions became a policy priority (Schneider et al., 2008; DDNI, 2008). In 1990 the Danube Delta along with its upstream floodplain, the Razim Sinoie lake complex, and the Black Sea coastal water zones were declared a Biosphere Reserve and granted protected status in accordance with the International Convention for the Protection of the World Cultural and Natural Heritage (1990), the Ramsar Convention of Wetland Zones of World Importance (1991), and the International Biosphere Network of UNESCOs Man and Biosphere program (1998).

Studies and projects for ecological restoration were started in the Danube Delta immediately following its declaration as Biosphere Reserve in 1990 (Schneider, 2010). An ecological restoration program started in 1993, focusing on degraded and inefficiently used agricultural lands, forestry polders, and fish ponds (Staraş, 1994). A management master plan comprised area to be restored and the agricultural polders Babina (2 100 ha) and Cernovca (1 560 ha) were selected as pilot project areas. The reconnection of polder Babina, formerly used for agriculture, to the flood regime of the Danube in 1994 was followed by the reconnection of Cernovca polder in 1996. In 2000, WWF promoted an agreement between Bulgaria, Romania, Moldova and Ukraine to restore 2 236 km^2 of floodplain to form the Lower Danube Green Corridor (DDNI, 2008), intended to attenuate floods, restore biodiversity, improve water quality, and enhance local livelihoods (Ebert et al., 2009). Restoration projects have also been implemented at the

Furtuna Forest East-West (2 115 ha), the Popina II fish polder (3 600 ha), and at the fishing polders Holbina I / II (4 370 ha) and Dunavăţ II (1 260 ha). In all, restoration projects to improve water circulation and connectivity through cleaning of fishery channels have been completed over a length of 494 km of aquatic complexes of the Danube Delta (DDNI, 2018).

A grant from the newly established Endangered Landscapes Program will be used to fund the Delta's largest transboundary restoration project to date with the aim of accelerating the recovery of natural landscapes, their ecological processes and associated flora and fauna across at least 40 000 hectares of the Danube Delta Biosphere Reserve (Rewilding Europe, 2018).

3. Methods

Our classification of ecosystem services and the definition of indicators was developed from a literature review and then discussed and validated in a scientific conference followed by a field visit of the research team to the Danube Delta and a workshop with local and international experts.

3.1 Classification and categorization of ecosystem services

First, a preliminary classification of ecosystem services was drafted from a review of literature, including both the broader literature on wetland ecosystem services and on-site research assessing ecosystem services at the Danube Delta, whether the term was used explicitly or not. Reviewed literature included peer review papers, books, policy documents, management plans, technical reports and PhD dissertations. We followed the international classifications of the Millennium Ecosystem Assessment (MA, 2005) and The Economics of Ecosystems and Biodiversity (TEEB, 2010) to classify ecosystem services in four major types: i) provisioning; ii) regulating, iii) cultural, and iv) habitat/supporting services. This general classification was subsequently refined followed guidance from technical reports dealing with classifications and categorizations of ecosystem services that are specific for wetlands and floodplains (MA, 2005; de Groot et al., 2006). When applicable, ecosystem services were classified in categories and subcategories. For example, the category food production in turn included the subcategories fishing, agriculture and animal rising.

The geographical scale of importance of each ecosystem services was then categorized as i) local, ii) regional, iii) or national to global, depending on the societal scale at which their benefits accrue. Ecosystem services categorized as local included those that are primarily oriented towards local use and livelihood such as collection of medicinal plants or sense of place and community. Ecosystem services categorized as regional included those traded primarily in regional markets (like reed production) or effecting regional culture or ecology, such as hydrological regulation and flood regulation. Finally, ecosystem services categorized as national to international included those with social and cultural value being recognized by governmental or intergovernmental treaties (e.g. habitat provision as recognized in the Ramsar convention) or that are traded in national or international markets, like food production. For ecosystem services embedding several sub-categories, the geographical scale of importance was determined by averaging the geographical scale of importance of the sub-categories it contains.

The preliminary classification drafted from the literature review was discussed at the international conference 'Restoration of wetland fragmented ecosystems' held on 8-10 October 2015 in Tulcea, Romania, and then validated during a field visit to the Danube Delta and workshop hosted the same month by the Danube Delta National Institute. The workshop gathered an interdisciplinary group of international and local scientists and practitioners with long-term research or working experience in the study area, including hydrologists, biologists, environmental scientists, social scientists and managers.

3.2 Definition of indicators

Assessment frameworks increasingly distinguish ecosystem service capacity, from flow and demand, to refer respectively to the potential, actual use and social expectations on ecosystem service supply (see e.g. Villamagna et al., 2013; Baró et al., 2016). The focus of our assessment is on flow, defined as "the ecosystem service actually received, used or experienced by people" (Villamagna et al., 2013: 116).

Indicators were defined for each ecosystem service category and subcategory, choosing those with best level of accuracy within available data. When data based on direct measurement was not possible, proxy measures were used, such as area of land use-cover providing a given ecosystem service. Where quantitative data were not available or failed to capture ecosystem services in a meaningful way, as in the case some cultural services (Chan et al., 2012), data from qualitative descriptions were used. When information gaps, low data quality, or inconsistency across sources impeded conclusive evidence, uncertainty was acknowledged. Uncertainty in indicators and data was labelled as low, medium or high for each ecosystem service category and subcategory. Criteria used for this classification included the level of precision of the indicator (e.g. direct measurement vs. land use-covers or other proxies), the quality of the sources (e.g. grey literature vs. peer-reviewed publications), and the level of consistency of information across consulted sources (e.g. high vs. low variance in data provided by different studies).

Trends are defined here as changes in ecosystem service condition and supply over time. When data were available, assessment of ecosystem services trends was conducted for the period 1960-2010. Motivations to choose this period were that i) it covers a timeframe that is meaningful to inform environmental decision making and planning, ii) it is largely consistent with the time frame used in the MA (1955-2005), which facilitates comparison with global and sub-global assessments, and iii) it covers a period that is long enough to capture changes in ecosystem services. When data were not available for these exact dates, available data from the most approximate date or period were used and specified. When possible, trends were assessed separately for the periods dominated by policies of economic development (1960-1989) and ecological restoration (1990-2010). When understanding present ecosystem service condition required adopting a broader time frame (e.g. large-scale interventions leading to disruption in the delta's sedimentary balance date back to the 19th century), the relevant time frame was indicated. Following the Millennium Ecosystem Assessment (MA, 2005), trends were classified as i) increasing, ii) stable, and iii) decreasing.

4. Results

A total of 13 ecosystem services and 10 sub-services were identified, described and assessed as the most important ones provided by the Danube Delta, including four provisioning services, five cultural services, three regulating services, and one habitat/supporting service. Four ecosystem services were categorized as holding national to global importance, including food production, tourism and recreation, science an education and habitat provision and biodiversity conservation; seven hold regional importance, including fresh water supply, raw materials, art and culture, spiritual values, nutrient cycling, erosion control /sedimentary balance and hydrological regulation / flood control; and another two are of primary importance to local communities, including medicinal plants and sense of place and community. A summary of ecosystem services identified and described for the study area, their geographical scale of importance, the indicators defined for their assessment, and the level of uncertainty of data is provided in Table 1.

[INSERT TABLE 1 ABOUT HERE]

Our assessment shows a generalized pattern of ecosystem service decline, particularly severe for regulating and habitat services. Data reviewed for our assessment indicate that nine out of the 13 services assessed (69% of the total) have declined over the studied period, including medicinal resources, recreation and tourism, art and culture, sense of place and community, spiritual values, nutrient cycling, erosion control and sedimentary balance, hydrological regulation and flood control, and habitat provision) whereas only four services (30%) increased their supply: food production, freshwater supply, raw materials, and science and education. However, in the latter group some ecosystem services may have increased in flow at the expense of declines in their stocks or potentials. For example, water harvest has increased but water storage capacity has declined. Trends vary markedly across categories, with regulating and habitat services appearing as the most severely affected. A summary of ecosystem services trends over the studied period is provided in Table 2.

[INSERT TABLE 2 ABOUT HERE]

In what follows, we provide a more detailed description of each ecosystem service together with data on their condition and trends over the studied period.

4.1. Food production

Fishing is a key resource for the delta's population. Fisheries are exploited across 315 000 ha of wetlands, including lake, river, marine coastal and anadromous fisheries. At least 136 harvestable fish species have been described in the Delta. Most important commercial species include carp, bream, perch, sturgeon and shad (Năstase and Năvodaru, 2008; Năstase and Staraş, 2015). Captures in the Delta's fisheries have been estimated to yield between 5 000 and 10 000 t/year, equivalent in value to 6.3 million US$, making it one of the most important inland fisheries in Europe (Năvodaru et al., 2005). Approximately 15 000 inhabitants within the Delta and a further 160 000 from adjacent regions depend fully or partly on fishery resource (Năvodaru et al., 2001). Commercial catch in the Romanian part of the Delta declined from about 15 000 to 5 000 t/year between 1960 and 2010 (Năvodaru et al., 2005; Năvodaru and Năstase, 2011) (Fig. 2). Last available data report annual fish yields of around 2000 t/year for 2014. The decline in fish catches is attributed to habitat loss, channelization, damming, navigation, pollution (especially nutrients and heavy metals), alteration of sediment transport, decreased connectivity, overfishing, and exotic species (Oosterberg et. al., 2000; Năvodaru et. al., 2005, EC, 2010; Wolter et.al., 2013). Today, the policy of the DDBR Authority is to restore fish habitats. About 15 700 ha of wetlands have already been restored and 9 230 ha of fish ponds were connected to the natural hydrological system. The aim is to restore 60 260 ha to natural conditions (Năvodaru et. al., 2005). A first assessment of restored areas suggests positive response of fish populations (Năstase and Staraş, 2015).

[INSERT FIGURE 2 ABOUT HERE]

Fig. 2. Trends of fish catch at the DDBR (1960-2010). Source: Redrafted from Năvodaru and Năstase (2011).

Agricultural land at the Danube Delta extended across some 40 000 ha by the end of the study period (2010) (Lup et al. 2017), consisting mostly of cash crops. In addition, most households grow vegetables, typically including potatoes, onions, garlic, peppers, greens, tomatoes, small cucumbers, plum trees, beans, maize and sunflowers (Bell et al., 2001). Although modern agricultural exploitation dates from 1939, large-scale agriculture in the Delta started after 1960, when large areas of wetland were reclaimed, and cultivated area peaked in the early 1990s. Data from Lup et al. (2017) indicate that cultivated area remained overall stable between 1965 and 1993 at about 62 000 ha, and then decreased to 40 000 ha by 2010, suggesting a stable supply in the economic development period followed by a decline in the conservation period, during which many non-profitable crops were gradually abandoned. Data is however inconsistent across sources. The Tulcea County Direction for Agriculture (2016) indicate an increase of arable land from 30 252 ha in 1996 to 43 075 ha in 2015, and an average annual yield ranging between 3-4 t/ha in the period 2000-2015. Crop area distributed as follows: barley 19.55 %, rape 14.84%, wheat 14.79 %, sunflower 13.41%, fodder plants 13.29%, maize: 5.61%, vegetables (soya been, potatoes, been, water melon, strawberries) 4.06 %, and oats: 0.27 %. The remaining 14.18 % of the land, salinized, gleyic soils, consisting of unseeded land. The total surface of cultivated non-arable land amounted to 18 106 ha by 2015, out of which 97.9 % was covered by orchards and vineyards, 1.5 % by pastures, and 0.6 % local householders, with the remaining 1,5% consisting non-cultivated land (Tulcea County Direction for Agriculture Annual report (2016).

Another important source of food supply is livestock rising. The program for the development and full operation of the Danube Delta approved in 1983 planned to reach 20 000 cattle, 350 000 sheep, 120 000 pigs and 350 000 poultry, but upon the presentation of the Reservation Management Project (1993), only 19 000 cattle, 60 000 sheep and 45 000 pigs were declared as livestock (Lup et al., 2017). Villagers keep cattle, sheep, pigs, geese, chickens, turkeys and ducks for subsistence. Most households have at least one milk cow. A few villagers keep bees and trade honey with their neighbors (Bell et al., 2001). Before banning, hunting provided additional income and food for locals and was economically important in winter. Thirteen species of mammals and 37 species of birds – mainly ducks and geese – were hunted for fur and meat (Marinov et al., 2012).

4.2. Fresh water supply

Fresh water supply is defined here in terms of water quality and quantity from the Delta's surface and groundwater, used for irrigation, industry and domestic use. According to Rauta et al. (1992), water abstraction for domestic, agricultural and industrial use increased 13-fold in the 1950-1989 period. This rising trend in water use is consistent with data from Lup et al. (2017), which refer to a major increase in the use of water for irrigation between 1960 and the mid-1980s. While we could not find data on water use for this period, data on land embanked for irrigation seem to confirm this trend. Data from Gâştescu et al. (2008) indicate that only 7000 ha had been embanked in the period 1953- 1965, while by the end of the period 1983-1989, 85 983 ha had been embanked and drained, out of which, 39 974 ha consisted of agricultural land, 6 442 ha consisted of forestry areas, and 39 567 ha consisted of fish polders (Fig. 1).

The Tulcea County Land Reclamation Administration reports a decrease in the use of water for irrigation from 550 to 386 million m^3 between 1984 and 1989, followed by a collapse down to 6.5 mill m^3 in 2010, as a result of changes in land ownership and increased exploitation costs following removal of subsidies after 1990. Hence, water extraction increased in the development period and decreased in the conservation period, with consulted sources indicating an overall increase over the studied period.

When it comes to quality, the Danube Delta is deficient in access to good drinking water (Nichersu et al., 2018). Local residents of areas lacking running water consume untreated water directly from the Danube after boiling. In areas lacking centralized water supply, schools and town halls have their own deep wells with variable water quality (MDRAP, 2016). Groundwater, found at depths of 2-5m, is rich in substances from decomposition sediment, such as sulfides. Only 60% of the rural population consumes good quality drinking water from greater depth, while the other 40% consume water directly from the Danube, water fountains or small depth springs that often do not comply with legal water quality standards. While the maximum allowable concentration of nitrates according to Law. 458/2002 is 50 µg/l, monitoring by the Public Health Departments of Tulcea and Constanta, have found nitrate levels to reach values up to 200 µg/l in water distributed through the centralized system (Nichersu et al., 2018).

4.3. Raw materials

Local villagers have traditionally used reed (*Phragmites australis*) as construction material for housing (roof making, fencing, matting and wall lining) and manufacture of household goods (carpets, furnishment, curtains, shelves or bowers for greenhouses), but also as fuel and as animal feed (de la Cruz, 1978; Pons, 1992; Covaliov et al., 2010). Commercial exploitation of reed in the Delta developed into large-scale exploitation during the 1960s to produce cellulose (Gâştescu et al., 1998). Government target plans reached the order of 2-3 million t/year. However, yields peaked in the mid-1960s and declined sharply thereafter as reed beds were destroyed from harvesting with heavy equipment. Pons (1992) report annual yields of 226 000 t in 1965, 55 000 t in 1975 and 33 000 t in 1992. De la Cruz (1978), report yields of 125 000 t in 1978 and Gâştescu et al. (1998) report a yield of 40 000 t for 1993. Despite variation, all sources indicate a sharp increase of reed harvest between 1960 and 1965 followed by a sharp decline.

Timber from the Delta's woods have been traditionally used for the construction of houses and tools. Most fish cottages are built on a frame of willow wood rafters, with the walls and the roof made or covered with reed. One of the main traditional craft activities was building wooden boats for fishing (IUCN, 1992). Nowadays, exploited forested areas in the Danube Delta consist preponderantly of willow and poplar that, due to their low quality as building materials, are only as firewood. Local building materials still include timber, but mostly imported from other areas of Romania (DDNI, 2013).

4.4. Medicinal plants

At least 123 species of medicinal plants have been recorded in the Danube Delta (Munteanu, 2002). In some parts of the Delta, such as the two old forests Caraorman and Letea, medicinal and aromatic plants are still collected by locals. The most widely collected plants are *Matricaria recutita* and *Hippophae rhamnoides* (Covaliov et al., 2012). Official data can be a poor indicator of actual harvest since the fees to be paid for the collection permits are unpopular and tend to be by-passed. As illustration, in 2002 the Biosphere Reserve authorized the collection of 11 761 kg of medicinal and aromatic plants while permit requests amounted to 15 kg only (Baboianu, pers. comm., cited in Kathe et al., 2003). A survey for 2002 estimates annual harvest of medicinal and aromatic plants at 15 t per year, distributed as follows: Matricaria recutita 10 t, Hippophae rhamnoides (flowers) 2 t, Symphytum officinale (fruits) 2.5 t, and Gypsophila paniculata (rhizomes) 0,5 t. About 70% of this material is estimated to enter the national market and 30% are sold on local markets. Nothing is exported (Kathe et al., 2003). These figures are broadly consistent with data by Munteanu (2002), who estimate annual harvest at 15,8 t. No data were found regarding trends. However, the decline of local population and traditional practices (Bell et al., 2001) hint at a decline in the collection and use of medicinal plants in the Delta, in line with trends that have been assessed both at global scale (MA, 2005) and elsewhere in Europe (Reyes-Garcia et al., 2015). It should be noted that this decline in ecosystem service *flow* (harvested plants) follows a decline in demand, and that it does not necessarily reflect a decline in ecosystem service *capacity* (plant abundance).

4.5. Recreation and ecotourism

Ecotourism is a fast growing sector in the Romanian tourism industry (Light and Dumbrăveanu, 1999). Since its declaration as a Biosphere Reserve, the Delta has been promoted for tourism, including water sports and bird watching (Hall, 1993; Gâşescu and Ştiucă, 2008). However, tourism is highly regulated, and large areas are inaccessible to tourists (e.g. strictly protected areas and buffer zones). Revised data report 15 tourism routes on waterways and 9 trails. Official data report 135 businesses licensed to conduct tourist activities on the DDBR and 400 different types of accommodations. Accommodation offer and the number of beds is estimated to almost triple officially reported numbers. In recent years, the supply of tourist activities has been diversified, including accommodation, meals, and traditional and artistic programs (Nicula and Spânu, 2016). Over the communist period, more than half of visitors came from abroad. The number of foreign visitors decreased sharply over the decade following the collapse of regime but then increased again since 2004, amounting to about one third of the total visitor by the end of the study period (Romanescu et al., 2012). Tourism peaked in the late 1970s and then declined in the 1980s as the state turned priority to large-scale land reclamation programs for agriculture, forestry and fisheries at the expense of investment in tourism. Decline continued over the 1990 but since 2002 tourism is recovering due to programs by the Romanian Government and European Union to finance tourism infrastructure. Overall, the numbers show a decline of tourism during the study period, from around 120 000 visitors over the 1970s to around 70 000 by 2010 (Romanian Ministry of Tourism 2018) (Fig. 3).

[INSERT FIGURE 3 ABOUT HERE]

Fig. 3. Trend in the Danube Delta Biosphere Reserve number of tourists (Source: National Institute of Statistics, www.insse.ro/cms/en).

4.6. Arts and culture

Nature's importance for local art and culture is reflected in the Delta's architecture, handcraft and folklore. Traditional homes are built of clay bricks, reed roofs and wood, the available resources in the area. Traditional house walls are made of adobe (clay mixed with straw and dried in the sun) on a wooden framework covered with reeds, although these are being gradually replaced by new materials like asbestos and galvanized iron for roofs (Boja and Popescu, 2000). Zoomorphic and naturalistic architecture in the Delta is abundant and varied. Wooden ornaments used in houses include horses, roosters, rabbits, birds, seahorses, and fish. Naturalistic elements are sometimes represented in mythological ways, such as a snake of two heads. Weaving rush is an old tradition in Delta. Its core and leaves have been traditionally used to manufacture baskets, boxes, hats, bags or mats. Handmade braided rushes are valued for their lightness and diversity of shapes and sizes.

A review of arts-based activities in the Delta by Văidianu et al. (2014) identified a wide variety of events and products, including festivals, celebration of church patrons, traditional fishing tools, practices or products, reed harvesting tools, traditional means of transport, traditional sports and customary social structures. Assessing trends in local art and culture involves differentiating tradition as practiced by and for the local population from tradition practiced for tourists, as studies in other European wetlands have shown that the former may decline while the latter increases (see Gómez-Baggethun et al., 2011b). In the Delta cultural and folkloric events for tourists are growing while those to locals seem to be declining.

4.7. Sense of place and community

Residents of the Delta stem from 17 different ethnic groups that have co-existed in the area for centuries (Pârâu, 2012), often developing shared identities shaped by the Delta's geography and options for subsistence (Teampău et al., 2008; Van Asche et al., 2008, 2012). Food culture and daily rhythms in the delta villages are tightly associated to fishing. Bell et al. (2001) note that local fishermen share occupational solidarity based on the shared mastery of unique skills and local knowledge, and they argue that the social cohesion that emerges from such a distinctive way of life outweighs the differences from ethnic and religious affiliations. However, Gog (2009) reports that emergence of new religious movements at the fall of the communist period unleashed tensions among ethnic and religious groups in the Delta. He contends that community fragmentation brought new rules for community exclusion and inclusion that carried conflicts around religious rituals like burials and the location of cemeteries.

Collected data does not allow assessing a clear trend in sense of place and community. However, decline in traditional professions (Bell et al., 2001), acculturation (Pârâu, 2012), and tensions unleashed by new religious movements (Gog, 2009) suggest a decline over the studied period. An important sign of acculturation is the vanishing of local ecological knowledge, practices and beliefs. Knowledge and skills for crafting and repairing fishing tools like nets persist mostly among the elders and few young people are willing to take over traditional activities. Much of the younger generation has left the Delta and reed huts are being replaced by concrete buildings. Traditional clothing is neither preserved, not even for holidays and ceremonies (Pârâu, 2012).

4.8. Spiritual values

The Delta is a node of spiritual diversity, expressed in multi-ethnic and multireligious communities, including Turks, Tartars, Macedo-Romanians and Slavs (Boja and Popescu, 2000; Bell et al., 2001). Due to its geographical and political isolation, the Delta has historically been a refuge for religious minorities like the Lipovans (Van Assche et al., 2008). In the 19th century the European Danube Commission sponsored churches from all religions practiced in the area contributing to a period of religious tolerance during which spiritual pluralism flourished (Iordachi and van Assche, 2014). In the 1950´s promotion of atheism by the communist regime brought about a decline in religious practice (Gog, 2009). The fall of the regime brought the emergence of new religious movements but, as elsewhere in Europe, religious practice seems to decline (Bell et al., 2001).

Anthropological research suggests that spiritual beliefs towards nature persist among some villagers, especially with regard to agriculture and fishing (Pârâu, 2012). Religious service to bring rain is customary in villages afflicted by draught. Research reports a religious service officiated by a priest for sanctifying the fishing tools when the fishermen go fishing for the first time in the year or season (Pârâu, 2012). New forms of spirituality are also emerging in connection to the modern conservation movement. Bell et al. (2001) note that the Delta evokes pseudo-religious sensibilities concerning the idea of landscape as a sanctuary for the protection of biodiversity. Viewed as a special place where wildlife is to be rendered safe from the effects of human activity, the biosphere reserve is somewhere set apart and hedged around with rules and taboos. In this sense there are parallels to be drawn with sacred spaces dedicated to religious purposes, even though the purpose of the biosphere reserve is formally secular.

It is difficult to assess an overall trend in spiritual values. However, decline in traditional rites and beliefs in relation to nature indicates an overall decline over the studied period.

4.9. Educational and scientific values

The first writings about the Danube Delta natural heritage and species date from antiquity, through the writings of Herodotus, Eratosthenes, Strabo, Ptolemy etc. In modern times a wealth of literature on the delta has been produced, including books and journal articles describing its geographical, geological, biological, agricultural, hydro-technical, and economic importance. At present, the most frequent themes are biodiversity status, habitat conservation and protection, natural resources, and recreational and aesthetic values. Since no data were found for the number of educational projects, visits and excursions, we used number of publications per year as an indicator of trends in the Delta’s educational and scientific values. A search on the Scopus database using the search terms (Danube) and (Delta) gave a total number of 391 publications for the studied time period, and the detailed numbers for the 5-year time intervals in Fig. 4 show a clear increasing trend. An additional 1040 secondary documents for the time period 2001-2010 are listed in Scopus. These are documents that are not available in the Scopus database, but are extracted from references lists in Scopus documents.

[INSERT FIGURE 4 ABOUT HERE]

Fig. 4. Number of scientific publications in on the Danube Delta.

4.10. Nutrient cycling

Pollution from agriculture (50% of the load), cities (25%) and industry (25%) makes the Danube the largest source of nutrients into the Black Sea, which suffers from a hypoxic 'dead zone' near the coastal zones (Behrendt, 2008). The Delta performs important functions of nutrient cycling (Gren et al., 1995). Floodplains' nutrient cycling capacity is intimately related to the communities of macrophytes that remove nutrients from the water column through filtering (Gómez-Baggethun et al., 2011a). While no data on phosphorous (P) and nitrogen (N) removal were found, previous research on the ability of shallow wetlands to retain nutrients situate nutrient cycling rates at 100 g/ha/year (Gren et al., 1995).

Concentration of P and N in the delta increased between 1960 and 1990 due to intensive agricultural activity, leading to water eutrophication (Uhel et al., 2010). Recorded amounts of N and P in coastal waters in the Black Sea increased between 1983 and 1988. Consulted data indicate an increase in inorganic N flowing into the Delta from 113 000 t in 1961 to 176 000 t in 2003. Organic P entering the delta was estimated at 5 500 t in 1961 and at 44 000 t in 2002 (Năstase and Năvodaru, 2008). After 1990, economic collapse in socialist regimes resulted in reduced pollution levels at the Delta entrance and the Black Sea. Average values from data collected at the Sulina Arm indicate a decrease in N-NH4 from about 0,480 mg/L in 1984 to about 0,220 mg/L in 2015. Dissolved P concentrations, PPO4, for the same period, oscillate between 0,190 mg/L and almost zero, with average values declining from 0,065 mg/L in 1984 to about 0,040 in 2015. Since the 1980s there is hence a decreasing trend in both N and P concentrations (DDNI 2008, unpublished data) (Fig. 5). Overall, nutrient cycling capacity seems to have declined over the studied period from the destruction of reed beds.

[INSERT FIGURES 5a and b ABOUT HERE]

Fig. 5a Nitrogen from ammonia concentrations in the Danube's arm - Sulina (1984 – 2015).

Fig. 5b Dissolved phosphorus concentrations in Danube's arm, Sulina (1984 – 2015). Source: Redrafted from DDNI reports – unpublished data

4.11. Erosion control and sedimentary balance

The DDBR hydrographic network consists of more than 3 500 km of lakes and channels. In lakes, erosion is prevented by dense vegetation (especially large surfaces of reed beds) but in channels high water velocity (1.00 – 1.50 m/s and faster during floods), has increased erosion rates, especially along the Danube's channels directly connected to arms. Erosion risk is considered to be high for about 7 % of channels, medium for 1.5 %, and low for 15.5 %, and very low for the remaining 76 %, since water velocity is low and the channel benches are covered with dense vegetation (DDNI, unpublished data).

A study covering the 1857-1989 documents increases of the Delta surface at the Black Sea coastal zone occurred as result of the Danube River high sediment discharge (about 0.0105 km^3/year deposition volume up to 10 m sea depth) and the sea-level decrease. However, at present the Danube Delta surface is decreasing with an average rate of 15 mm/year as result of the Danube River low sediment discharge from damming (about 0.0185 km^3/year erosion volume up to 10 m sea depth) and of sea-level rise with a rate of about 2.5 mm/year (Bondar, 2004a). Prior to 1960 (1921-1960) the amount of sediments carried by the river at the delta entrance was estimated at 67.5 million t/year (2 138 kg/s) (Bondar and Blendea, 2000). Thereafter, and especially following the construction of the two hydropower dams (1969-1984), annual average sediment discharge decreased to 29.2 million t/year (926 kg/s) within 1981-2000 (Bondar, 2004b) (Fig. 6). The delta is receding due to erosion, which is affecting wetlands and coastal zone. A chronic sand deficit extends downdrift of the delta coast, and the loss of bathing beaches threatens an important tourist economy at the southern sector of the Romanian Black Sea shore (Giosan et al., 1999). With the purpose to diminish the Black Sea shore erosion, by increasing the water flow speed /water and sediment discharge, within 1982 - 1992 the length of Sf. Gheorghe arm was shortened from 108 to 65 km after the six meanders on its course thereby corrected (Cioacă, 2002, 2004). Overall, reservoirs, dams and barrages regulating the discharges of the Danube river, and channeling of meanders have disrupted the natural discharge and circulation of sediment on the coastal zone of Danube Delta (Dan et al., 2007), indicating that the sedimentary balance and erosion control functions have been heavily disrupted over the studied period.

[INSERT FIGURE 6 ABOUT HERE]

Fig. 6 Trend in sediment discharges to the Danube Delta within 1960 and 2000 (Bondar, 2004a). Legend: R input (kg/s) at the Danube Delta entrance, R output (kg/s) at the Danube's mouth – Black Sea, and R sediment discharge (kg/s) into the Delta's inner hydrographic network. Source: Bondar, 2004b.

4.12. Hydrological regulation and flood control

While the Delta still held a 'natural' hydrological regime, the flooding area covered 3 510 km^2 and most of the channels connected the main fluvial arms (Chilia, Sulina and Sf. Gheorghe) to the great lacustrine complexes. Hence, lacustrine complexes had the capacity to absorb the water excess in the river, thereby performing important functions of water regulation and flood control. After 1956, however, hydroengineering works impaired the water circulation system, causing the disruption of hydrological regulation processes (Uhel et al., 2010). Many channels were straightened and made very shallow, which led to the clogging of the lacustrine cuvettes and to the blocking of the access paths, consequently reducing capacity for flood buffering. Baboianu and Staraş (1993) estimate the flooding area affected by hydro-technical engineering at about 4 000 km^2 that became isolated from the Danube River hydrological pulse and flooding dynamics. Under the altered hydrological regime, the flooding area has been reduced to 1 030 km^2, less than one third of the flooding area under the natural regime.

Water level at the Danube River fluctuated between 0.11 and 5.14 masl, as measured at the Tulcea port gauge in the 1858-2010 period (Bondar, 2004; Tulcea Hydrological Station, unpublished data). To assess water storage capacity along this range of fluctuation, we used data on stored water volume (million m^3) and flooded surface (ha) measured before and after large-scale alteration of the hydrological regime in the 1960s at low, medium and high water levels, corresponding respectively to 1.5, 3.5, and 5 masl. Data indicates that flooded surface and stored water volume declined from 190 870 to 130 820 ha and from 1 814 to 1 267 million m^3 for the low water level; from 275 000 to 185 849 ha and from 4 332 to 3 508 million m^3 for the medium water level; and from 309 470 to 206 400 ha and from 6 188 to 4 329 million m^3 for the high water level (Gâştescu and Știucă, 2008), indicating a decline in water storage capacity.

The Delta is flooded every year. The historical analysis of the maximum discharge of the Danube in Tulcea port records large river discharges in 1895 (13 700 m^3/s), 1942 (13 387 m^3/s), 1970 (14 520 m3/s), 2006 (15 900 m^3/s) and 2010 (16 600 m^3/s) (Bondar, 2004b; Niculescu et al., 2015; Popescu et al., 2015). Romanescu and Stoleriu (2014) point to flood risk as the most important economic and technical issue for the Delta. The delta's floodplain and coastal wetlands were seriously impacted by floods in 2002, 2005, 2006 and 2010. Most vulnerable areas are the localities situated in the fluvio-maritime delta, along the arms, affected by both the increase in the water level and by the emergence of the phreatic level of coarse sands (Romanescu and Stoleriu, 2014). In the spring of 2006, high water levels in the Danube lasted for over 6 weeks (April– June 2006). Over 30,000 people were displaced in the entire basin of the Danube River, and damages were estimated at over 500 million € (Gan et al., 2012). The floods of 2010 affected several villages of the Danube Delta. More than 16 500 people were evacuated and more than 45 000 ha of agricultural land and forests were submerged (Niculescu et al., 2015). From the above data, we conclude that water regulation and flood control services provided by the Delta have experienced a severe decline.

4.13. Habitat provision

About 523 km^2 of the DDBR are strictly protected zones as they provide habitat for a large number of flora and fauna species, especially those included in one of the IUCN Red List of Threatened Species categories (IUCN, 2012). The DDBR total number of species recorded within 1991-1995 is 5 380, out of which 1 839 flora and 3 541 fauna species (Otel, 2000). Within 1996-2015, the number of species recorded increased to 7 504, out of which 2 905 flora and 4 599 fauna species (Török, 2009, 2014; Török and Radu, 2007; Onără et al., 2014; Holostenco et al., 2012, 2013; Ferguson et al., 2000; Cioacă et al., 2009; Doroftei et al., 2011).

Number of species included in the IUCN Red List of Threatened Species categories having turned to red list status was used here as a coarse proxy indicating a decline in the supporting/habitat service 'habitat provision'. The reason is that most drivers of biodiversity loss identified in the literature such as pollution, overharvesting, land use change, and infrastructure development, involve some sort of habitat degradation. Hence, it is assumed that more red listed species signals degradation of habitats, that in turn signals a decline in habitat provision. Within 1995-2015, the number of red list species increased compared to previous study interval, from 343 to 732, corresponding to the increase of number of species recorded within the last study interval (Marinov et al., 2012; Goriup et al., 2007). These data show an increase of number of species included in the IUCN Red List of Threatened Species categories, having turned to red list status between 1996 and 2010. (Fig. 7), indicating an overall decline of habitat provision. As noted in Table 1, however, the assessment of this service is subject to a large level of uncertainty.

[INSERT FIGURE 7 ABOUT HERE]

Fig. 7 Number of species at the DDBR included in the IUCN Red List of Threatened Species categories.

5. Discussion

5.1 Patterns in ecosystem services change

Overall, provisioning services have enhanced their supply over the studied period, whereas regulating and habitat services have declined, a picture that is consistent with the general pattern obtained for the global scale by the Millennium Ecosystem Assessment (2005), as we discuss below.

Ecosystem service trends vary markedly over the periods dominated by economic development and environmental conservation and restoration policies. Overall, data indicate that provisioning services like food production and raw materials increased markedly over the economic development period fostered by state-driven policies of economic development, and have thereafter declined both as a consequence the collapse of the communist regime and from regulations by conservation policies that prioritize ecosystem protection over resource exploitation. The reverse is true for most regulating and habitat services, which declined from the impacts of economic development policies but thereafter experienced some degree of recovery, either as a consequence of less pressure from economic development (as in the case of nutrient cycling, which benefited from the collapse of the national industry) or because of the merits of protection and restoration policies, as in the case of hydrological regulation and species conservation.

A decline in cultural services is also apparent but here the picture is more mixed. As it occurs worldwide in an era of economic globalization, growing market integration, and mechanization (Gómez-Baggethun et al., 2010), the rich body of traditional ecological knowledge, practices and beliefs held by the local communities as well as the local vernacular architecture declines as local communities integrate the national and global trade economy and adopt new technologies and lifestyles (Bell et al., 2001). Lack of generational turnover as younger generations migrate to cities and population decline add to the weakening of local culture. However, some cultural services such as ecotourism and new forms of spiritual values connected to nature are on the rise. For some services, trends can be better understood as qualitative rather than quantitative change. For example, a national-focused, state-driven tourism policy was replaced by an emerging market driven tourism industry that includes international tourists. Likewise, local art and culture declined from acculturation and depopulation, but some aspects of folklore and tradition have returned, albeit in highly commodified forms, as part of the tourism industry, which relies on local art, culture, architecture, and tradition as an appeal for tourists and visitors.

Our results are consistent with the patterns obtained in the global assessment produced by the Millennium Ecosystem Assessment (MA, 2005) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), which reports a decline for 14 of the 18 categories of ecosystem services analyzed (referred to as ‘nature’s contributions to people’ in the assessment report) (IPBES, 2019). Our results are also largely consistent with the findings of ecosystem assessments of other outstanding coastal wetlands of Europe, including those conducted in Doñana, Spain (Gómez-Baggethun et al., 2011b; Zorrilla et al., 2014) and in Tour de Valat, France (Uhel et al., 2010).

Despite strong evidence indicating a sharp decline in ecosystem services, results for individual ecosystem services should be taken with care due to the large degree of uncertainty involved (Table 1). Uncertainty emanates in some cases from the complexity of the ecosystem service being assessed, but also from lacking, incomplete or inconsistent data between the consulted sources. For example, data for provisioning services varied largely across sources and in some cases the actual amount of yield or land cover seemed to be conflated with the (often unmet) production targets set by the socialist regime.

5.2 Socio-environmental costs and benefits from ecosystem loss and restoration

Loss of wetland ecosystem services bears multiple unaccounted costs to society (TEEB, 2010). These socio-environmental costs can include "all direct and indirect losses sustained by third persons or the general public as a result of unrestrained economic activities" (Kapp 1977, p. 13). They can take the form of damages to human health, damage of natural or built capital, decreased livelihood opportunities, and impairment cultural, symbolic and other intangible values, among others. Some of these costs can be measured in money, for example by calculating the costs of replacing ecosystem functions through built infrastructure (e.g. water purification plants) or by calculating the costs of ecological restoration projects aimed at re-establishing good ecological condition. These costs rarely appear in company balance sheets or economic accounts, unless liability is claimed through court cases or unless state regulations mandate their internalization (Phelps et al., 2015). In practice, the bulk of these costs are shifted to future generations, the poor and other species (Martínez-Alier 2002).

When and whether restoration works will re-establish ecosystem functioning and capacity to sustain ecosystem services and associated benefits is uncertain, not least because wetland function restoration involves large economic time lag costs (Gutrich and Hitzhusen, 2004). However, previous research on wetland restoration suggests that benefits from most restoration projects can largely outweigh their costs (Loomis et al., 2000; Peh et al., 2014, Elmqvist et al., 2015). From a review of over 200 studies, De Groot et al. (2015) conclude that coastal wetlands are among the ecosystems that yield most value for restoration investment, even if wetland restoration typically involves very capital-intensive projects.

Given the short time passed since the implementation of the first restoration projects in the Danube Delta linked and the long time that is typically required to restore ecosystem functions, the effects of restoration in ecosystem services and benefits are still largely uncertain. However, Ebert et al. (2009) suggest that ecological restoration work started in the Delta in 1993 has already provided important benefits, including improved capacity to retain and release floods and remove pollutants (e.g. from the growing extension of reed), enhanced biodiversity, and strengthened local economies through diversification of livelihood resources (for example from economic activities related to research and tourism). Data collected at the Babina and Cernovca restoration areas indicate that the restored reed beds act as important biofilters for nutrient retention and cycling (Schneider et al., 2008).

Some attempts have been made to estimate economic benefits from the restoration of the Delta. A first attempt by Gren et al. (1995) estimated the value of fish provision, forestry, animal fodder, nutrient retention and recreation at 383 € per ha/year. Based on Romanian expert estimations for nutrient reduction, provision of fish, reeds, crops, vegetables, animals and tourism, Kettunen and ten Brink (2006) estimated the economic benefits for the restored lower Danube at 1 354 € per ha/year. Schwarz et al. (2006) estimated economic benefits from nutrient reduction at 870 € per ha/year. Based on these highly differing economic values, an average value was calculated to be approximately 500 € per ha/year (Schwarz et al., 2006) for provision of ecosystem services for fisheries, forestry, animal fodder, nutrient retention and recreation through floodplain restoration (see Ebert et al., 2009). However, given the complexity of treating the long-term values of the result of restoration, these data are subject to large levels of uncertainty and should be treated with caution.

Although restoration projects are a first important step to reverse declining trends in ecosystem services, it should be noted that in terms of the amount of land (area) affected, the scale at which restoration measures have been implemented is not yet comparable to the scale of the area that was negatively by economic development policies. Sources consulted for this study situate the area of the Delta transformed by development projects in the range of 100 000 ha (Tulcea County Direction for Agriculture, 2015). By contrast, all restoration projects implemented in the Delta up to date affect around 10 000 ha (see figures provided in DDNI 2018), meaning that the areas affected by development and restoration still differ by an order of magnitude. Arguably, larger and longer-term ecological restoration efforts will be required before the ecological condition and ecosystem services of the Delta can return to levels comparable to those existing before the 1960s. The restoration of ecological processes and associated flora and fauna across at least 40,000 hectares of the Danube Delta planned in the Endangered Landscapes Program (Rewilding Europe, 2018) can be a major step in this direction and holds potential to reduce the existing gap between degraded and restored areas in the Delta.

Last but not least, it should be noted that the alleged positive trend in ecosystem services and benefits following restoration measures in the Delta applies only locally. From a global sustainability perspective, it remains an open question whether restrictions in economic uses of the Delta may have leaked to other, more distant areas. For example, restrictions for food production to supply the national market may have resulted in increased food imports, involving environmental cost-shifting to the areas where food is now being produced. Such off-site effects from ecosystem service protection policies, also referred to as 'ecosystem service burdens' (Pascual et al., 2017), should be an important topic for future research to allow situating local ecosystem assessments in a broader global sustainability context.

6. Conclusions

Knowledge and data synthesized in this paper shows that the Danube Delta is an area of global importance for ecosystem service delivery, which benefits to people accrue from the local to regional and global scales. For local communities, the Delta is a fundamental source of livelihood and income; for Romania and Ukraine, it is an area of strategic economic importance for resource extraction and ecotourism. For humanity at large, it is an outstanding node of biocultural diversity and heritage.

Decades of unfettered economic development policies in the Danube Delta have led to a severe degradation of about one third of what arguably is Europe's most outstanding wetland. Besides its well-known ecological impacts, findings from our research indicates that about two thirds of the Delta's services have declined since the 1960s, regulating and habitat services being the most severely affected. The Danube Delta offers a paradigmatic example of how land use change and continued exploitation of provisioning services above natural regeneration rates impairs the ecological functioning on which their long-term delivery ultimately depends. Mounting exploitation of provisioning services in the Delta over the second half of the 20th century occurred at the expense of severe declines in regulating and habitat services. Furthermore, marked declines in yields of reed and fish resulting from habitat degradation illustrates the prophecy of the ecosystem service framework, namely that continued damage of habitat and regulating services to maximize the delivery of provision services ultimately compromises the long-term capacity to sustain provisioning services themselves. In other words, in the long run unsustainable economic exploitation of ecosystems undermines the ecological foundations for the economy itself. Ongoing ecological restoration projects is a first important step to reverse these trends and, despite the large uncertainties involved, research reviewed in this paper indicates that ecological restoration policies implemented since the 1990s have started to deliver important social, ecological and economic benefits.

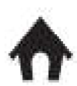
To our knowledge, this is the most wide-ranging assessment of ecosystem services provided at the Danube Delta wetlands to date. We hope this paper will provide insights to scientists, practitioners, decision-makers, and planners on the effects of development and restoration policies on ecosystem services, deriving lessons from the past to make better decisions in the future. We believe that our results can serve as an important input for ongoing ecosystem service initiatives, including the global and regional assessments of IPBES, research initiatives by the Ecosystem Services Partnership (ESP) working groups, and international initiatives for inclusive wealth accounting that corrects for loss of ecosystem services.

Acknowledgements

This research was funded through a European Economic Area grant (EEA, www.eeagrants.org, www.eeagrants.ro), in the framework of the “Restoration of aquatic ecosystems in the Sontea-Fortuna area component of Natura 2000 sites of the Danube Delta Biosphere Reserve” [RESTORATION-DD] project, 2015-2017, http://restoration-dd.ddni.ro), and the “Demonstrating and promoting natural values to support decision-making in Romania” (N4D) project (2015-2017). Data were kindly provided by the project partners, DDNI (Tulcea, Romania), The Norwegian Institute for Nature Research (NINA), and DDBRA (Tulcea, Romania). Gómez-Baggethun also received partial funding from the OpenNESS project (European Community’s7th Framework Program under grant agreement 308428) and from a grant of the talent development program of the Norwegian University of Life Sciences (NMBU).

Table 1.
Ecosystem services classification, description, geographical scale of importance, indicators, and level of uncertainty in data and information.

Ecosystem service category	*Sub-category*	*Description*	*Ecosystem service beneficiaries*	*Geographical scale*	*Indicator for measurement*	*Level of uncertainty*
Provisioning services		*Physical goods obtained from nature*				
Food production 		Portion of gross primary production extractable as food substance and trade	Consumers in local, national and international markets		Land use-cover for food production (ha) or harvest (t/year). Large variation in data	++
	Fishing	Fish and shellfish from inland and coastal waters, wild and from aquaculture, for trade and subsistence	15 000 locals and 160 000 from adjacent regions depend fully or partly on the Delta's fisheries		Fisheries area (ha) or fish harvest (t/year)	+
	Agriculture	Cash crops and subsistence agriculture, including cereals, vegetables, fruits	Local farmers and consumers in local, national and international markets		Cultivated area (ha) or crop harvest (t/year)	++
	Animal farming	Animal rising in farms and pastures for production of meat and dairy products	Local farmers and consumers in local and national markets		Pastures area (ha) or production of meat and dairy products (t/y)	++
Fresh water 		Precipitation collected by rivers, lakes, aquifers and other bodies for water supply	Local people using water for domestic use and irrigation		Extracted water in m^3, area of irrigated land, and nitrate levels (μg/l)	++
	Water for domestic use	Water for drinking, washing and cooking	Domestic water supply for local populations		Nitrate levels (μg/l) t measure quality	++
	Water for irrigation	Water for irrigated arable land	Local farmers and consumers of food products		Area of irrigated lands (ha), or water extraction (m^3/y)	++
Raw materials 		Materials from plants and animals for direct use or processing, including wood, timber, and fibre	Users purchasing products in local and national markets		Area exploited for raw materials (ha) or harvest (t /year - m^3/year)	+

	Reed	Reed harvesting for cellulose and by-products, including hardboard	Users purchasing products in local and national market		Area covered by reed (ha) or harvest (t /year, m^3/year)	+
	Timber	Timber production for construction of houses, tools, and boats	Users purchasing products in local and national market		Area covered by woods (ha) or timber harvest (m^3/y)	++
Medicinal resources 		Plants holding biochemical substances; medicinal uses from herbs	Local people		Number of plants with known medicinal uses or quantity of collected herbs (tons/year)	++
Cultural services		*Immaterial benefits obtained from interaction with nature*				
Recreation and ecotourism 		Eco-tourism and outdoor recreational activities: sport fishing, field trips, nautical sports, programs for children, photo safari, sun bathing	Tourism industry: local tour operators, restaurants and hotels. Benefits to local people and tourists from other regions and countries		Number of tourists visiting the area per year	+
Art and culture 		Use of nature as motive in art, culture and folklore; nature in sense of place and community	Nature in books, painting, art, folklore, architecture, national symbols, and festivals		Diversity and presence of cultural traits	++
	Folklore	Nature in local tradition, including festivals, music, dances, art and architecture	Local people, tourists and the tourism industry		Number of festivals / year	++
	Architectur e	Zoomorphic and naturalistic traits in traditional architecture and use of local materials	Local people, tourists and the tourism industry		Number of traditional buildings and use of traditional materials	+
	Historical values	Archaeological sites or items with historical value	Local people, tourists and the tourism industry		Number of archaeological sites	+
Sense of place and community 		Identifying oneself in relation to a place and community contributes to strengthening social cohesion and resilience	Local people		Markers of cultural identity like clothing, architecture, traditions etc. Social cohesion and lack of conflict	++

Spiritual values 	Use of nature for religious or spiritual purposes and contemplation. Role in shaping local values	Local people, including various religious minorities. Visitors approaching nature through contemplation	●	Number of spiritual cults and religious ceremonies practiced in the area	++
Science and education 	Education, knowledge creation, and scientific development	Local schools. National and international scientific community	⬤	Number of scientific publications on the Danube Delta per year	+
Regulating services	*Benefits humans derive from ecological regulation processes*				
Nutrient cycling 	Storage, cycling, processing and acquisition of nutrients to maintain water quality and improve soil fertility	Local people depending on water supply from the Delta. Local farmers and consumers of food products	●	Area covered by reed (ha) or flow of N and P (t /year)	+++
Erosion control /sedimentary balance 	Prevention of loss of soil by wind, runoff, or other removal processes, storage of silt in lakes and wetlands. Formation and maintenance of beaches	Local farmers and consumers of food products. Visitors and industry related to beach tourism	●	Area covered by the delta (ha); solid discharge transported by the river and its main arms	+++
Hydrological regulation and flood control 	Ecosystem damping response to water fluctuations reduces likelihood for human casualties and injuries, and for damage on built infrastructure	Local people, especially inhabitants of settlements along the river floodplain	●	Flooding area as proxy of water collection capacity (ha)	++
Habitat services	*Provision of habitat for species along their life cycle*				
Habitat provision 	Provision of habitat for plants and species and maintenance of ecosystem resilience and associated insurance value	Resource users using and harvesting species. Existence and option value for humanity at large	⬤	Number of red listed species	+++

Source: Own elaboration with icons by Jan Sasse for TEEB (except for icons 'science and education' and 'sense of place and community'). Size of the dots indicate geographical scale of importance of ES categories (black dots) and sub-categories (grey dots) where ⬤ = national to international; ● = regional; • = local. + indicates level of uncertainty in data and information, where + = low; ++ = medium, and +++ = high level of uncertainty

Table 2.
Assessment of ecosystem service trends in the Danube Delta over the period 1960-2010

Ecosystem service category	***Sub-category***	***Comment***	***Development period***	***Conservation period***	***Overall trend***	***Sources***
Food production 		Ambitious plans were developed in the planned economy period to increase food production but were only partially implemented. Agricultural area remained stable in this period but productivity increased, while fish production decreased. A decline in agriculture followed in the 1990s with removal of subsidies	⬆	⬇	⬆	Uhel et al., 2011; Lup et al., 2017
	Fishing	Catches decreased from over 15 000 to 5 000 t /year in 1960-2000 due to channelization, damming, land use change, pollution, overfishing, and exotic species.	⇔	⇩	⇩	Năvodaru and Năstase, 2011
	Agriculture	Starting in 1939, agricultural development was promoted by the communist regime (1947-1989) peaking at 100 000 ha at its fall. Later, agriculture declined markedly to around 60 000 ha.	⇔	⇩	⇩	TCDEA, 2015; Uhel et al., 2011
	Animal farming	Animal farming increased during the communist period. Within 1990-2000, area devoted to pastures remained stable at 22 500 ha.	⇧	⇔	⇧	Uhel et al., 2011; Lup et al,. 2017
Fresh water supply 		Water abstraction for domestic, agricultural and industrial use increased 13-fold in the 1950-1989 period, from, and then decreased abruptly.	⬆	⬇	⬆	Bondar 2004a
Raw materials 		Exploitation of the Delta for extraction of raw materials increased during the communist regime and declined after 1989. Overall, extraction of raw materials has increased in 1960-2010.	⬆	⬇	⬆	Uhel et al., 2011
	Reed	Large-scale reed production started in the 1950s but declined sharply since the 1960s due to reed rhizomes degradation from use of heavy equipment. Yield was 226 000t in 1965, 55 000t in 1975 and 33 000t in 1992.	⇩	⇩	⇩	Pons, 1992; Gâştescu, 1993; Lup et al., 2017

Timber	Within 1990-2000, 330 ha of transitional woodland converted to forest.	⇧	?	⇧	Uhel et al. 2011
Medicinal resources	123 plants with known medicinal uses recorded in the DD. No data for trends were found but decline of local population and traditional practices invites to think that the collection and use of medicinal plants in the Delta is declining as elsewhere in Europe	?	?	⬇	Danube Delta National Institute; Bell et al., 2001
Recreation and ecotourism	During the last fifteen years of the communist regime, the practice of hosting tourists in the homes of delta villagers declined. Land use allocated for sport and leisure facilities increased in 39 ha in the period 1990-2000, and ecotourism is increasing.	⬇	⬆	⬇	Bell et al., 2001; Uhel et al., 2010; Danube Delta National Institute, 2008
Art and culture	Lack of generational turnover as younger generations migrate to cities, population decline and decline of tradition contributes to the decline of local culture.	⬇	⬇	⬇	Van Asschen et al., 2008
Folklore	Decline with loss of tradition. In recent times, some revival of folklore related to tourism. Eighteen culture festivals organized yearly. The number of visitors during the festivals is increasing.	⇩	⇩	⇩	Văidianu et al., 2014
Architecture	Traditional architectural decoration or houses are less used after 1989 and are gradually replaced by modern style and materials.	⇩	⇩	⇩	Bell et al., 2001
Sense of place & community	All of the delta villages have a shrinking population. Population was estimated at 20 000 in 1966 and at 12 600 in 2011. Those who are left are predominantly elderly. After the fall of the communist regime religious tensions have affected social cohesion.	?	⬇	⬇	Bell et al., 2001; Van Asschen et al., 2008; Romania census data 1900 – 2011
Spiritual values	Religious practice declined over the communist period, but new religious movements appeared after its fall. The Delta's ecosystems evoke spiritual 'pseudo-religious' sensibilities concerning the idea of a sanctuary for biodiversity, which parallels sacred spaces.	⬇	⬆	⬇	Bell et al. 2001 Gog (undated)

Science and education	The number of scientific publications and projects, research permissions, and educational projects/visits increases continuously.	↑	↑	↑	DDBRA data/1993-2016; Mocior & Kruse, 2016.
Nutrient cycling	P (PO4) inflow increased from 100 to 1 400 t/year and N (NO3) inflow increased from 4 000 to 29 300 N (NO3) inflow t/year between 1960 and 1989, due to agricultural development and associated use of fertilizers. After the1990s, the collapse of industry in socialist regimes resulted in reduced concentration of P and N.	↓	↑	↓	Năstase and Năvodaru, 2008; DDNI 2008, unpublished data
Erosion control and sedimentary balance	Damming, dredging, and channelling disrupted erosion rates and impaired sedimentary balance. Decreased sediment discharge produces chronic sand deficit. The delta is receding as erosion increases along the coast.	↓	↓	↓	Bondar, 1990; Giosan et al., 1999, 2013; Romanescu and Stoleriu, 2014
Hydrological regulation and food control	Hydrological regulation is severely impaired by damming and dredging. Lacustrine cuvettes that absorbed water excess lost their function as channels led to the clogging of the cuvettes and to blocking of the access paths. Hydro-technical woks transformed about 400 000 ha.	↓	↑	↓	Romanescu and Stoleriu 2014 Baboianu and Staras, 1993
Habitat provision	Complete data series for the entire period of analysis were not found, but data for 1996-2015 indicate an overall increase of number of species recorded. The number of Vulnerable, Endangered, Critically Endangered and Extinct species turned to red list status has increased based on increased number of recorded species.	↓	?	↓	Otel et al., 2000, 2007; Torok, 2009, DDNI report 2010; Doroftei et al., 2011.

Source: Own elaboration with Icons by Jan Sasse for TEEB (excepting icons for 'Educational and scientific values' and 'sense of place and community'). ↑ = increased; ↔ = remained stable; ↓ = decreased, where large arrows in colour and the smaller arrows in grey signal trends of ecosystem service categories sand sub-categories respectively. ? = Not assessed due to lack of data and/or large level of uncertainty.