Alteration and Remediation of Coastal Wetland Ecosystems in the Danube Delta. A Remote-Sensing Approach

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Chapter
Alteration and Remediation of Coastal Wetland Ecosystems in the Danube Delta. A Remote-Sensing Approach

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Abstract Wetlands are important and valuable ecosystems; yet, since 1900, more than 50% of wetlands have been lost worldwide. An example of altered and partially restored coastal wetlands is the Danube Delta in Romania. Over time, human intervention has manifested itself in more than one-quarter of the entire Danube surface. This intervention was brutal and has rendered ecosystem restoration very difficult. Studies for rehabilitation/re-vegetation were begun immediately after the Danube Delta was declared a Biosphere Reservation in 1990. Remote sensing offers accurate methods for detecting changes in restored wetlands. Vegetation change detection is a powerful indicator of restoration success. The restoration projects use vegetative cover as an important indicator of restoration success. To follow the evolution of the vegetation cover of the restored areas, images obtained by radar and optical satellites, such as Sentinel-1 and Sentinel-2, have been used. The sensitivity of such sensors to the landscape depends on the wavelength of the radar or optical detection system and, for radar data, on polarization. Combining these types of data, which are associated with the density and size of the vegetation, is particularly relevant for the classification of wetland vegetation. In addition, the high temporal acquisition frequencies used by Sentinel-1, which are not sensitive to cloud cover, allow the use of temporal signatures of different land covers. Thus, to better understand the signatures of the different study classes, we analyze the polarimetric and temporal signatures of Sentinel-1 data. In a second phase, we perform classifications based on the Random Forest supervised classification algorithm involving the entire Sentinel-1 time series, proceeding through a Sentinel-2 collection and finally involving combinations of Sentinel-1 and -2 data. The supervised classifier used is the Random Forest algorithm that is available in the OrfeoToolbox (version 5.6) free software. Random Forest is an ensemble learning technique that builds upon multiple decision trees and is particularly relevant when combining different types

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of indicators. The results of this study relate to the use of combinations of data from different satellite sensors (multi-date Sentinel-1, Sentinel-2) to improve the accuracy of recognition and mapping of major vegetation classes in the restoring areas of the Danube Delta. First, the data from each sensor are classified and analyzed. The results obtained in the first step show quite good classification performance for only one Sentinel-2 data (87.5% mean accuracy), in contrast to the very good results obtained using the Sentinel-1 time series (95.7% mean accuracy). The combination of Sentinel-1 time series and optical data from Sentinel-2 improved the performance of the classification (97.1%).

Keywords: coastal wetlands, Danube delta, alteration and remediation of ecosystems, remote sensing, synergy of radar time series Sentinel-1 and optical image Sentinel-2.

1. Introduction

According to United Nations Environment Programme research, 40% of the global economy depends on the adequate functioning of ecosystems. Many ecosystems have been sacrificed in the name of economic development in various fields such as agriculture and other production systems and as a result of urbanization, industrialization, resource extraction, transportation and other infrastructures. Given the increasing number of anthropogenic perturbations of natural and semi-natural ecosystems worldwide, the mere preservation of these ecosystems is no longer sufficient. Ecological restoration may thus prove to be an essential complement to their preservation. The dramatic depletion of biological diversity and the degradation of ecosystem services allowed legitimizing a marked evolution of the international, European and Romanian political context. As a result, the preservation and restoration of natural ecosystems has been recognized to be essential and constitutes part of Romania’s future political commitments, more precisely of the National Biodiversity Strategy 2013-2020.

Over the past few decades, efforts to raise awareness of the environmental, functional and patrimonial interest of natural areas, as well as the evolution of protection policies, with a view in particular to the implementation of the “Habitats-Fauna-Flora” European Directive of 1992, have led to the carrying out of numerous ecological restoration operations. Ecosystem restoration is becoming a global priority at various levels of decision-making, with the goal of achieving specific political and technical objectives (Aronson & Alexander 2013).

2. Scientific Background

The concept and principles of ecological restoration emerged in Europe and in the United States of America at the beginning of the 20th century, the goal being to look after the “wounded landscape”. Thus, ecological restoration is a relatively new concept that has undergone considerable development over the last twenty years both at the theoretical level and at the level of concrete field applications. Additionally, in the last 10 years, the science and practice of the discipline have progressed significantly, generating knowledge, creating and applying tools, designing procedures and promoting networks worldwide. The first actions consisted of measures designed to control mountain land erosion and forest environment degradation. These actions have been extended and diversified to allow proper management of multiple environmental degradation situations in various natural environments. Certain systems may be restored directly according to the initial botanical composition theory; marshes or wetlands may thus be restored over a period of several years under optimal conditions. For other ecosystems, the process that takes place between the moment when they recover their self-regulating powers thanks to their restoration and the moment at which they achieve the environmental maturity stage of their target system is lengthy (decades or centuries).

In most cases, the ecosystem that needs restoring has been degraded, damaged, transformed or completely destroyed as a direct or indirect result of human actions. The human being who used to destroy without considering the consequences of his actions now wishes to repair the damage through the ecological restoration concept. Ecological restoration is an action that initiates or enhances the self-repair mechanism of an ecosystem and at the same time observes its health, integrity and sustainable development (Bouzillé, 2007). Restoration is generally thought to allow an ecosystem that has been degraded or destroyed by natural and/or human causes to resume its prior condition. The faithful recreation of original habitats still generates lively debate; many definitions of ecological restoration have been suggested, and other related terms such as rehabilitation and reallocation are also often used.

Ecological restoration is one of the means used to maintain ecosystem services and stop biodiversity loss. As a matter of fact, one of the objectives of the Convention on Biological Diversity (CBD) established during the Conference of the Parties held in Nagoya in 2010 was the restoration of at least 15% of the degraded areas worldwide by 2020. The Society for Ecological Restoration (SER) (2004) defines ecological restoration as “the process that could assist the regeneration of an ecosystem which has been degraded, damaged or destroyed”. Ecological restoration is an intentional activity designed to accelerate or restore a historic ecosystem in connection with the original resident species, the structure of communities, the functioning of the environment, and the ability to shelter living organisms and connect them with the surrounding environment (Aronson, 2010). This supposes and requires thorough knowledge of the functional and progressive ecology of the target ecosystems, of the history of the anthropogenic degradation of the ecosystem and, finally, of the choice of a reference ecosystem meant to guide the planning, implementation, follow-up and assessment of the restoration project (White and Walker, 1997; Egan and Howell, 2001). Restoration project guidelines (Clewell and Aronson, 2013) and practical guidelines (Perrow and Davy, 2002, a) have recently been developed, and more fundamental works have been published (Walker and del

Moral, 2003; Temperton and Hobbs, 2013; Walker et *al*., 2003; Suding and Hobbs, 2009).

Ecological restoration should become a priority so as to limit the process of degradation of the environment, to contribute to the preservation of fragile habitats and of critically endangered species and to ensure the valorization of natural resources. When the economic, social and cultural dimensions are taken into account, ecosystem restoration becomes a strong area of intervention for development actors. Thus, the major restoration and rehabilitation objectives are, as concerns ecosystems, the preservation or increase of their primary or secondary productivity and the improvement of their biological diversity and stability, and, as concerns landscapes, the support of their reintegration when they are severely fragmented. With a view to sustainable development and, in particular, to building a sustainable environment, the natural environment sciences have recently begun to develop approaches that combine the restoration or preservation of ecological processes and functions and the biodiversity and productivity of ecosystems with economic and social uses.

These restorations are currently the object of numerous projects that are more or less ambitious and more or less expensive. As a result, in addition to the willingness to maintain and preserve ecosystems, there is a certain pressure from society concerning the assessment of the success of ecological restorations. Many of these projects concern wetlands worldwide. The wetlands of the world provide more ecosystem services per area than any other habitat type (Costanza et *al*., 1997; Dodds et *al*., 2008). Wetlands are important and valuable ecosystems, yet, since 1900, more than 50% of wetlands have been lost worldwide. The loss of ecosystem services when wetlands are degraded or converted to other land use types is well documented, as are global rates of wetland loss that range from 30 to 90% by region (Dahl et *al*., 1990, 2011; Junk et *al*., 2012; Zedler and Kercher, 2005). Coastal wetland regions are under serious threat and have been suffering from severe degradation.

3. Restoration of coastal wetlands and the Danube Delta

The projects in wetlands are costly and achieve variable success. Although many coastal wetland restoration projects are conducted every year, wetland degradation has not been retarded worldwide because of the limited success in wetland restoration (Zedler, 2000). Wetland restoration refers to the return of wetland from a disturbed or altered status caused by anthropogenic activities to a pristine status (Mitsch and Gosselink, 2007; Jarzemsky et *al*., 2013). The degradation of coastal wetlands is often accompanied by direct or indirect changes in hydrology. Hydrology modification is more widely adopted as the appropriate hydro period, a key factor determining success in wetland restoration (Turner and Lewis III, 1996; Wortleyet et *al*., 2013; Jarzemsky et *al*., 2013). Chemical restoration refers to the removal of pollutants in inflow or the control of sources of pollutants in such a way as to restore the quality of coastal water and sediment (Wilcox and Whillans, 1999), whereas biological restoration targets restoring the microorganisms, vegetation and fauna of degraded wetlands. Vegetation studies provide insight into the effectiveness of restoring wetland ecosystem functions. Although governments have put much effort into coastal wetland protection practices, most wetland restoration projects focus on the restoration and regulation of vegetation, and there is a lack of systematic studies on the mechanisms of coastal wetland degradation and ecohydrological processes, especially hydrological and biological connectivity on a large scale (Harttera and Ryan, 2010). Therefore, ecohydrological environmental indicators need to be further integrated for successful evaluation of coastal wetland restoration based on the holistic restoration of wetlands (Ellison, 2000; Allen, 2003).

An example of altered and partially restored coastal wetlands is the Danube Delta in Romania (Figure 1).

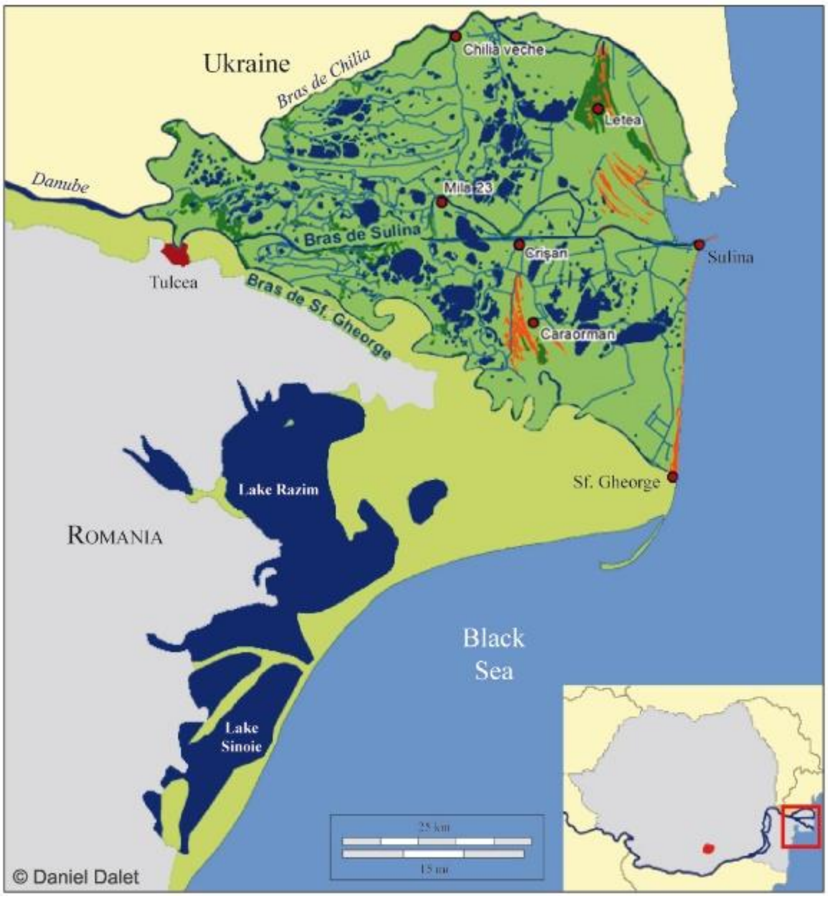

Figure 1: Danube delta. Geographic localization

The total area of the Danube Delta Biosphere Reserve is approximately 5 800 km^2 in Romania and more than 50 km^2 in Ukraine (Hanganu et al., 2002). In the

Romanian portion, the reserve includes the upstream Danube floodplain of Tulcea-Isaccea, the Razim-Sinoe lagoon complex and the marine coastal waters (20 isobaths). The Danube Delta itself refers to the area between the three main branches of the Danube River (from north to south, these are the Chilia, the Sulina, and the Sfântu Gheorghe (St. George) branches), which are located in Romania with a total area of 3 510 km^2. The Danube Delta is the third largest delta in Europe, after the Volga Delta (13 000 km^2) and the Kuban Delta (4 300 km^2). The Danube Delta, Romania's youngest landmass, is a fluvial-maritime floodplain covering two floristic provinces, the lower Danube (ponto-sarmatic) and the Black Sea (euxinic) (Ciocarlan, 1994). The diversified geomorphology, soils and hydrological conditions favor the proliferation of a large number of aquatic, semi-desert and saline habitats.

Each habitat is part of a unique nature conservation network. The flora in the Danube Delta Biosphere Reserve (both the Romanian and Ukrainian sectors) are characteristic of a steppe bioregion with a temperate climate featuring almost 1 400 species of vascular plants (Hanganu et *al*., 2002), of which five species (1 subspecies) are endemic (0.51% of the total number).

A vegetation map of the delta produced by [66] shows 44 types of vegetation grouped into 8 categories in the Romanian delta and a significant part of the Ukraine delta. These units consist of the following: flood plain forests, beach/sea vegetation and dune vegetation, salt-tolerant vegetation, sandy steppe meadows, river elevation meadows, dune forests, marsh vegetation and aquatic vegetation. Natural marsh vegetation and aquatic vegetation are the most widespread in the Danube Delta. Vegetation cover of this type occupies 398 676 ha within the delta, of which 362 965 ha is in the Romanian section and 35 711 ha is in the Ukrainian section (Hanganu et *al*., 2002). Reed marshes, covering more than 220 000 hectares, are by far the Danube Delta's dominant vegetation type. The dominant species is *Phragmites australis*, which is usually accompanied by hydrophilous species such as *Typha angustifolia*, *Schoenoplectus lacustris*, *Sparganium erectum*, and *Thelypteris palustris*. Most of the plant communities and species are terrestrial, and they can be found on the elevations and barrier beaches. Within the aquatic plant communities, the characteristic flora include Eurasian and circumpolar vegetation. The terrestrial plant community belongs to the Eurasian, continental, Pontic and Mediterranean classes.

Over time, human intervention has manifested itself in more than a quarter of the entire Danube surface. This intervention was brutal and has rendered ecosystem restoration very difficult. The ecological conditions of the Delta have also been influenced by the human activities carried out in the entire Danube basin: the building of flood plain dykes and dams, hydrotechnical accumulations, erosion control works and catchment works (especially for irrigation purposes) and development of economic activities in the Danube basin (industry, agriculture, energy, transportation, and other activities).

4. Improvements, Transformations and Alterations of the Danube Delta Ecosystems

Over time, the development of fluvial-maritime navigation and of resource use policies applying to the Danube Delta (fish, agricultural, forestry, etc. resources) has determined the main water system and landscape transformations in the delta. The first interventions in the water system of the Danube branches occurred in 1857-1858 after the creation in 1856 of the European Commission of the Danube (ECD) following the signing of the Treaty of Paris at the end of the Crimean War. The branch altered between 1857 and 1902 was the Sulina Branch in the central part of the delta. After the shortcuts in the meanders of this branch, in particular the "great M" (Dunarea Veche), the branch was shortened by 20.8 km, from 83.4 km to 62.6 km, and deepened from 2.4 m to 7.2 m, to allow the navigation of heavy-tonnage ships of up to 55 000 tdw. The alteration of the Sulina Branch also required the consolidation of the banks of the Danube and the building of a jetty at the entrance to the Black Sea. This jetty offers protection against clogging with sediments brought by the Chilia Branch. In 1895, also under the auspices of the European Commission of the Danube, a small marshy area next to the Mahmudia Locality and close to the Sfantu-Gheorghe Branch was altered for agricultural purposes. This area is also known as the "Gradinile franceze si olandeze[4]".

Other interventions in the water system of the delta date back to the 1900-1935 period, when, following the suggestions of the hydrobiologist Grigore Antipa, several canals were built to facilitate the flow of water between the Danube branches and the lake complexes within the delta or between these inner complexes and the Razim-Sinoe complex. The goal of these improvements was the enhancement of fishing productivity in a natural environment (Antipa, 1914). Some of the most important canals were built during this period, including the Dunavat (initially called Regele Carol I) in 1907, the Dranov (Ferdinand Canal, which connects the Sfantu Gheorghe Canal to the Razin-Sinoe complex) between 1912 and 1914, the Enisala (Elisabeta Canal) in 1913, the Litcov (Carol II Canal) between 1929 and 1932, the Crasnicol (Voeivodul Mihai Canal) between 1930 and 1934, and the Sireasa, which is parallel to the Sulina Branch connecting the Sontea-Furtuna Complex to the Danube branch (Figure 2).

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[4] The French and Dutch Gardens.

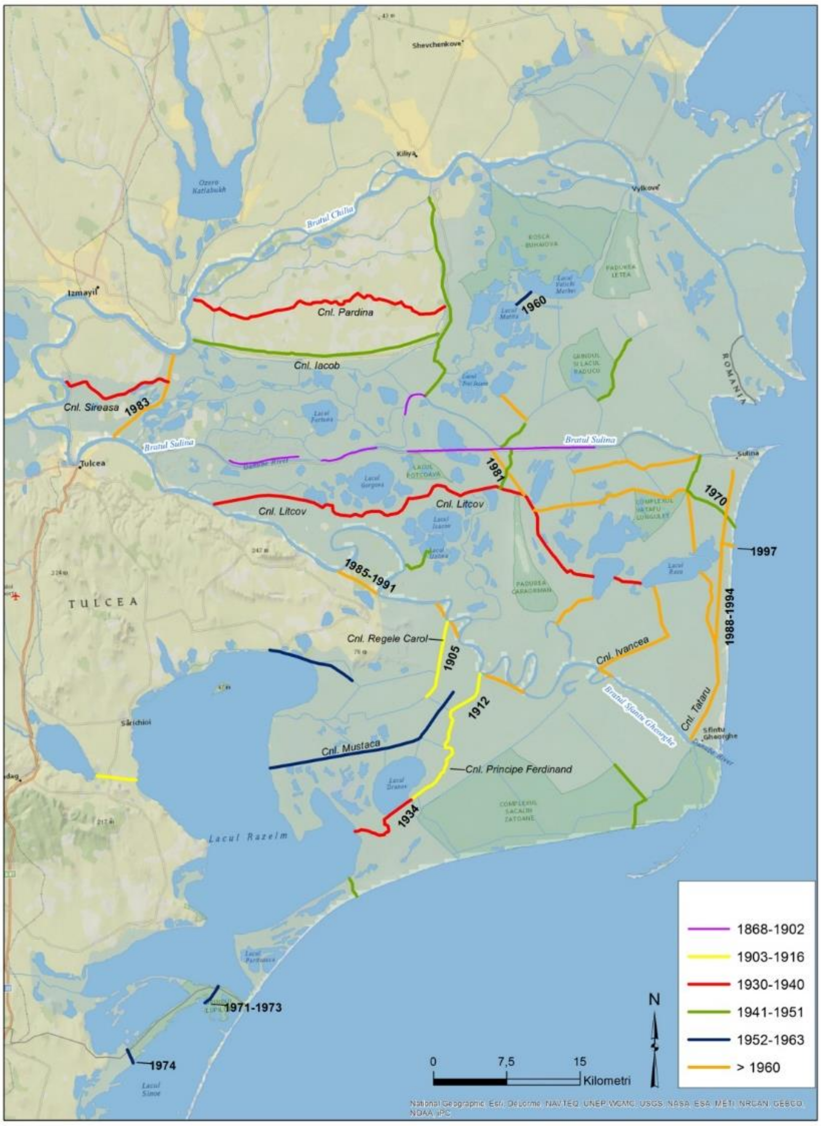

Figure 2. Chronology of the hydro-technical works in the Danube Delta during the 1900-1994 period. The most important canals built during this period: Dunavat (initially called Regele Carol I) in 1907; Dranov (Ferdinand Canal) between 1912 and 1914, which connects the Sfantu Gheorghe Canal to the Razin-Sinoe Complex; Enisala (Elisabeta Canal) in 1913; Litcov (Carol II Canal) between 1929 and 1932; Crasnicol (Voeivodul Mihai Canal) between 1930 and 1934; Sireasa, parallel to the Sulina Branch connecting the Sontea-Furtuna Complex to the Danube branch

Another alteration that may be traced back to before the Second World War is the Tataru Polder (2500 ha), a small, dammed, drained and irrigated island on the Chilia Branch; on this island, cereal production is considerable (up to 10 000 kg/ha of corn). The Magearu and Eracle-Batacu Canals between the Chilia and the Sulina branches were also built prior to 1950, as were the Rosulet-Garla Imputita and Buhaz Ciotic Canals between the Sulina Branch and the Sfantu-Gheorghe Branch and the Gotca and Iacob-Batacu Canals in the Pardina Depression.

All these hydrological interventions carried out in the delta were accompanied by changes in the deltaic landscape. The issue of the use of the reed (*Phragmites australis*) here was raised after the Second World War. An experimental research station designed to study the possible uses of the deltaic reed was set up in Maliuc in 1956. The main objective of this initiative was to alter certain depressions in such a way as to allow semi-guided reed growth and development (dammed depressions endowed with pumping stations designed to regulate the water levels depending on the height of the reed) and its subsequent industrial use. Other reed- and reed-use-related topics, such as reed physiology, the advantages and disadvantages of reed fires, the influence of heavy equipment (crawler tractors) on reed regeneration, the influence of dyke building on reed growth and development, etc., were studied at this experimental research station.

The Danube Delta reed had been used long before 1956 but in a traditional manner (on the ice, during winter, when the migratory birds had left the area and the fish took refuge in deep waters) without any intervention in the deltaic environment. Thus, the reed was used for construction purposes (roofs and fences), as a fodder supplement and even in the cellulose production process (a cellulose factory, which was destroyed during the war, operated in Braila between 1908 and 1916). After 1956, more precisely during the communist regime, reed was essentially used in the cellulose production process; therefore, the cellulose factory was rebuilt (1958) close to the town of Braila (Chiscani), approximately 100 km from the delta.

The 1960-1970 period, which is called the “reed age”, is also the first period of deeper alterations of the deltaic ecosystems. First, many canals were built, and the resulting alluvium was used to build 50 to 100 m-long and 2 to 3 m-high reed storage platforms above the Danube (Gastescu and Stiuca, 2008). In the 1960s, most of the polders were designed for reed use, in particular in the fluvial delta (eastwards); these areas included the Pardina depression, the loop of the great M (DunareaVeche) and the depression located west of the Caraorman levee, located between the Sulina and the Sfantu Gheorghe Branches. These polders were irrigated by pumping between March and October and were then drained for the end of autumn-winter harvesting. This decade saw the peak of reed production in the Danube Delta. Thus, reed production reached 226 000 tons in 1965, decreased to almost 100 000 tons in the 1970s and did not exceed 20 000 tons in the 2000s.

What could be the explanation of this drop in reed production in the Danube Delta? One of the most plausible explanations, which is adhered to by many authors, is that the use of heavy machinery to harvest the reed destroyed its rhizomes. Other possible causes have also been suggested: reduction in the reed's regeneration and natural drainage period and diminution of the sediments and nutrients in the water pumped into the altered depressions. Several opportunistic hydrophilic species such as the cattail (*Typha sp.)*, the rush (*Juncaceae* family) and the sedges (*Carex sp.*) appeared at this time and took advantage of the situation, proliferating to the detriment of the reed.

Due to the failure of reed processing in the delta, several reed-processing facilities (Rusca, Balteni, Maliuc, Obretin) were converted to fish-farming developments. In fact, the 1970-1980 decade is considered to be the period of fish farming development in the delta. The 1980s were marked by the passing of a decree by the State Council in 1983 (Programme for the Full Development and Exploitation of the Natural Resources of the Danube Delta) according to which a considerable part of the delta was to be altered for agricultural purposes (crops and farms for animal husbandry), and the development of fish and forest exploitation was to be extended. Thus, the delta and the Razim-Sinoe lake complex were divided and shared among six business ventures exploiting delta resources. These ventures were subordinated to the Danube Delta Office seated in Tulcea (DDO).

A whole set of fish farming developments were subsequently created during that period, including the Popina, ChiliaVeche, Stipoc, Dunavat, Holbina I, Holbina II, Periteasca, and Ceamurlia developments, which together occupy approximately 40 000 ha. The fish farming system suggested for the delta was a closed one, which meant that all the feed had to be supplied by the livestock farmers. Things did not progress as expected because, due to economic recession after 1973, maintenance and servicing of the water supply and drainage facilities became difficult; consequently, fish production did not measure up to the initial investment. Some authors (Gastescu, Stiuca, 2008) note that the location of these fish farming developments was not very wise to begin with. Either they were located on fertile land suited for agriculture (Stipoc), the soil salinization brought about by these alterations led to the extension of the French tamarisk species *(Tamarix gallica)* (Popina II, located eastward of the Letea levee), or the peat in the soil was harmful to the fish fauna (Holbina I and Holbina II, located between the Razim Lake and the Dranov Lake) (Figure 3).

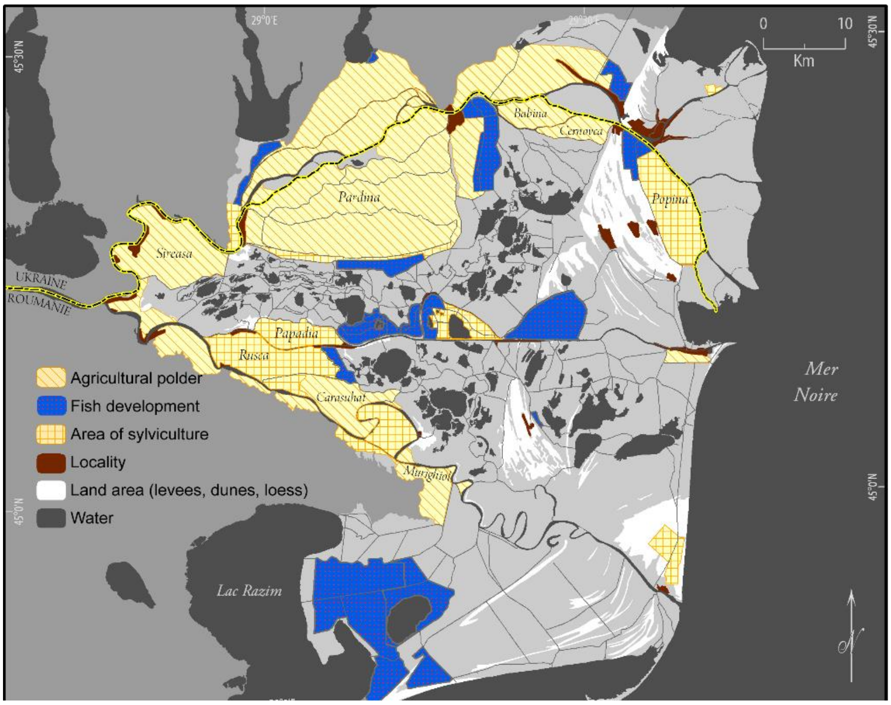

Figure 3: Various Danube Delta improvements prior to 1994. Over time, human intervention has manifested itself in more than a quarter of the entire Danube surface.

There are 5 agricultural development areas in the Danube Delta Biosphere Reserve, with an overall surface area of 39 974 ha; these are located in various places in the reserve on the territory of 5 communes (table 1).

	Locality	**Agricultural development**	**Surfaces/ha**
1	Ceatalchioi	Sireasa	5 480
2	ChiliaVeche	Pardina	13 766
		Tataru	2 061
		Total	15 827
3	Mahmudia	Carasuhat	2 863
4	Murighiol	Dunavat-Murighiol	2 538
5	Pardina		13 266
	Total area of agricultural developments		39 974

Table 1: Agricultural developments and their surface areas

This intensive delta development period saw the setup of the many agricultural developments that still exist on the right bank of the Sfantu Gheorghe Branch from Tulcea down to Mahmudia. These agricultural developments do not significantly influence the ecological balance of the delta because there are few lakes and marshes in this area. These developments are considered profitable from an agricultural point of view. The Pardina and Sireasa developments, which are located in the fluvial part of the delta (Figure 4), are considered to be the most radical.

Figure 4: Example of agricultural development in the Sireasa polder (top) and example of fish farming development in Caraorman (bottom). Photos S. Niculescu, September 2010.

27 000 ha of the Pardina polder, which make up 10% of the deltaic plain and 67.62% of the agricultural development area of the delta, were fully altered (in the 1960s this depression was developed for fish farming) for agricultural purposes in 1983. This time, the natural landscape and the natural water flow disappeared completely after the major development works conducted here (drainage canals, irrigation canals) (Figures 5 and 6).

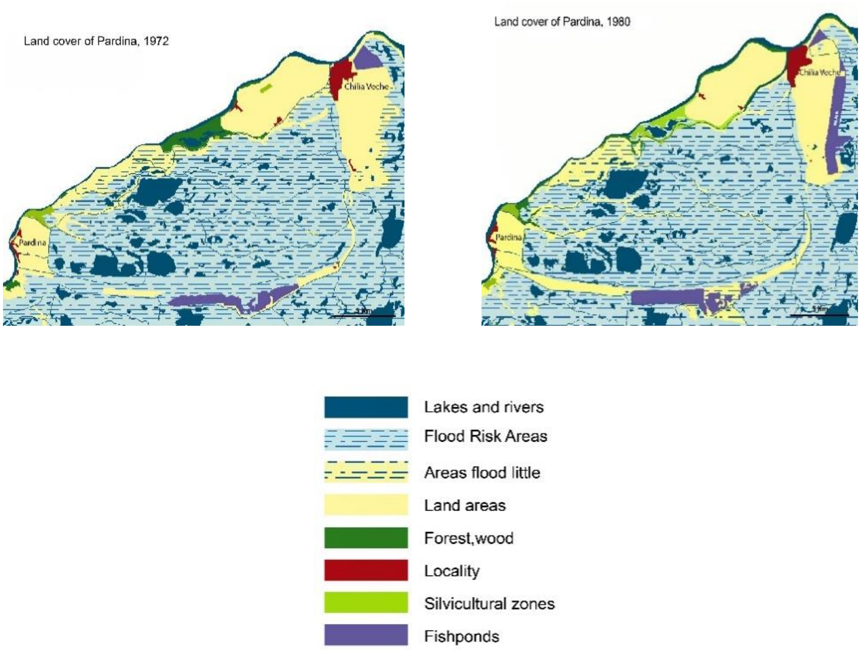

Figure 5: Land cover of Pardina.
Data Source: topographic map 1 / 100 000, 1972 (left) and 1 / 25 000, 1980 (right)

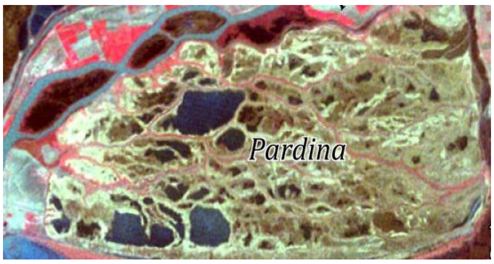

Figure 6: Land cover of Pardina. a) Data source: Landsat-2 MSS, 23/04/1979. Pardina before the transformation in polder agricol. b) Data source: ALOS AVNIR-2, 10/06/2010. Polder agricol af Pardina after the the fall of communism.

Thus, five intensive agriculture farms were created in the Pardina polder. They had the following land use structure: 84.32% tillable land, 15.46% grassland and 0.2% vineyards and orchards. Legally speaking, 95.3% of the polder's surface area is currently included in the public domain managed by Tulcea County Council, and only 384 ha are owned by Pardina Commune inhabitants. The former Public Agricultural Company (IAS in Romanian), which owned the exploitation rights during the communist regime, was privatized after 1989. Nevertheless, the resulting private companies soon went bankrupt, and the land became the property of the County Council. The policy consisted of granting concessions to private investors for large pieces of land by public tenders (Niculescu et *al*., 2015). The County Council is accused of not taking into consideration the local specificity of Pardina and of giving away the land too easily, the farmers' only obligation being to practice only agriculture on that land. These changes attracted many foreign (French, English, and Italian) investors, who took over the farming of more than two thirds of the polder. Additionally, several shepherds who came to Pardina from Transylvania during the communist regime progressively took up the southern part of the polder. The development of the Pardina polder has raised problems for the local and county authorities because they do not share the same vision. The ecological or economic benefits have taken the spotlight, and the local population seems to have been forgotten in these development projects, although the local population should be the most important topic in discussions of the sustainable development of the land where they live. The scientists working for the National Danube Delta Research Institute support the idea of flooding the polder and restoring it to its initial state, i.e., its state prior to the 1960s. The researchers working in this institute claim that a considerable portion (50-60%) of this polder is not cultivated and that crop rotation is not performed properly, with the result that the crops harvested here are quite small in comparison to the investments that have been made. However, the most clear-cut position on this issue is that of the Tulcea General Council. According to this council, polder flooding is merely utopian. They claim that the flooding would ruin Pardina's economic environment and lead to further degradation of the standard of living of the local population. Each year, the General Council collects several hundreds of thousands of Euros in concession fees. One of the problems that make the application of this project difficult is the fact that compensations would have to be paid to the polder farmers if they are expropriated. The Romanian Government has tried to find solutions to this problem, but given the current crisis, this project is no longer considered a priority (Niculescu et *al*., 2015).

7 550 ha of the Sireasa polder have undergone similar radical agricultural development (Figure 7). Such development has also occurred in Murighiol-Dunavat (on the Sfantu-Gheorghe Branch) (Figure 10) as well as in Babina and Cernovca (located on the Chilia Branch) (Figure 8), where the development involves smaller areas intended for rice production. This type of developpement also includes the polder Popina (Figure 9).

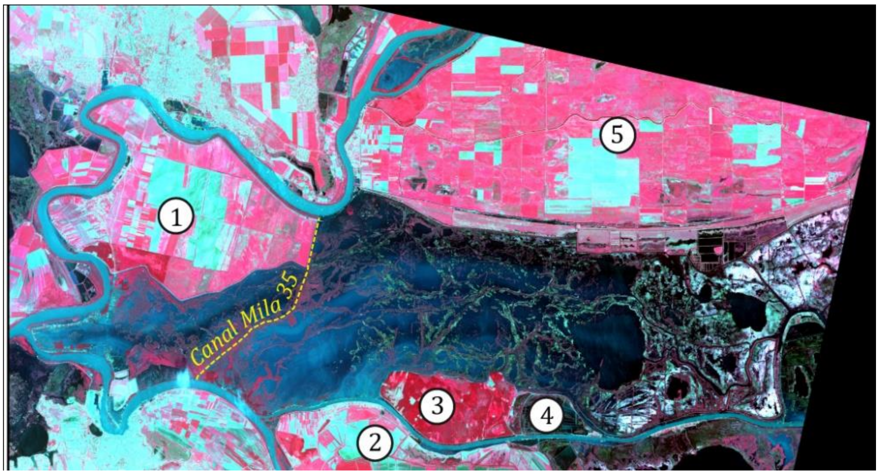

Figure 7: Agricultural development in the northeastern part of the delta: 1) Sireasa development; 2) Rusca development; 3) Papadia development; 4) Maliuc development; 5) Pardina development. Data source: SPOT-5, 23/05/2006.

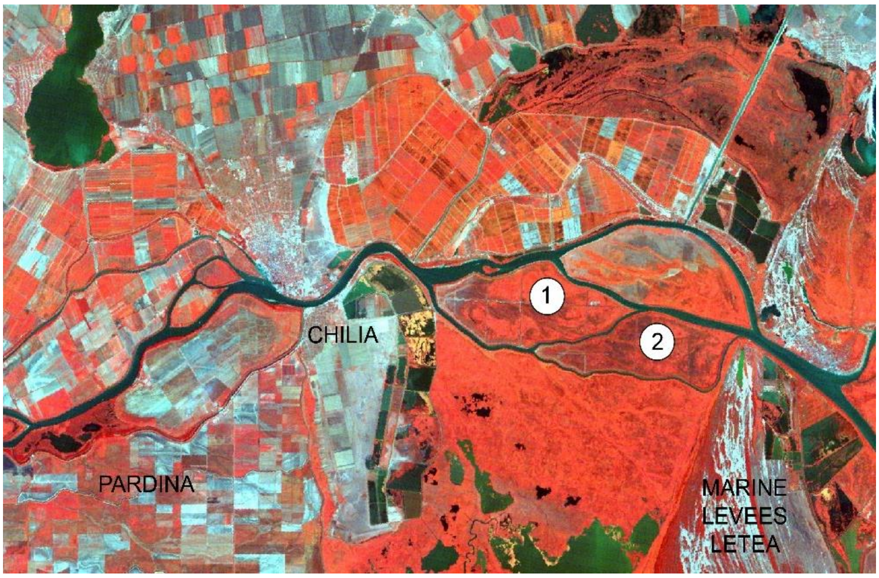

Figure 8: Babina (1) and Cernovca (2) agricultural developments before the restoration sites. Data source: Landsat TM5, 21/05/1992.

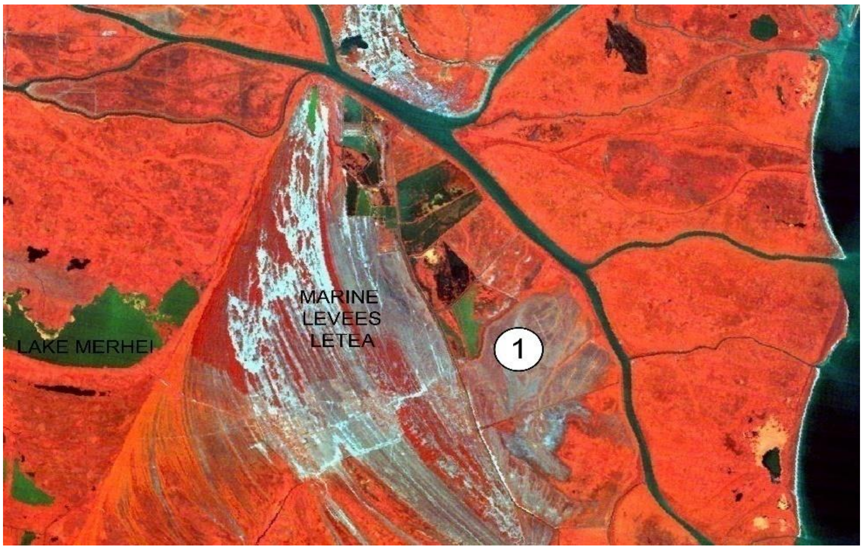

Figure 9: Popina fish farming and agricultural development before the restoration site. Data source: Landsat TM5, 21/05/1992.

Figure 10: Holbina-Dranov fish farming development. Data source: Landsat TM5, 20/08/1989.

According to various studies conducted by the researchers of the National Danube Delta Research and Development Institute, only 40% of the whole Murighiol-Dunavat polder was originally cultivated, whereas most of the surface of this polder is covered by organic deposits. The various studies carried out at that time (I. Munteanu, 1979) clearly noted the major difficulties encountered during the improvement of the quality of these soils; these include desiccation/drainage, soil salinization prevention and control, land leveling, soil texture homogenization, soil acidity problems, and reed removal problems.

The hydrological factor is the main aspect that disturbed the ecosystems of the spaces that were altered for agricultural purposes during the communist regime. The changes in the natural hydrological regime brought about by dykes have resulted in a series of physical and chemical changes in the soils and in the vegetation structure. In turn, these changes triggered changes in local fish and bird fauna habitats. The main alterations that were carried out here were damming and construction of a network of desiccation canals (hence, a substantial modification of the water circuit in these areas) and the replacement of wetland plants with agricultural crops, leading to profound changes in the vegetation structure and composition, marsh soil degradation (organic matter loss), increased soil salinity, reduction in the number of bird habitats, and loss of the filtration role of sediments and nutriments.

In the areas of concern, forestry developments are quite small in comparison to agricultural developments; the former only occupy 4 650 ha. Canadian poplar plantations (*Populus canadensis*) are present in the Papadia, Rusca, Carasuhat, Pardina and Murighiol developments or along the main Danube branches. These plantations have reduced flower diversity, reflecting reduced delta biodiversity, and have led to the degradation of the forest ecosystems, especially those of the Letea and Caraorman forests.

All these developments, together with the full delta resources exploitation policy, have also stimulated the construction of canals around these facilities of economic interest. Examples of such canals include the Crisan-Caraorman canal connecting the Sulina branch and the Caraorman locality, where a sand exploitation facility was designed (nevertheless, this industrial facility was never built), the 10-km Mila 35 canal connecting the Tulcea and Chilia branches, which allows communication with and transportation to localities along the Chilia branch, other branch-straightening works designed to facilitate reed transportation, water supply in the fish farming developments and water supply for irrigation purposes. One of the last large changes during the communist regime occurred on the Sfantu-Gheorghe branch, which was straightened between 1985 and 1990; during this process, its length was reduced by 38 km from its original length of 108 km. The straightening of the branch, which was accomplished by shortcutting six meanders, has increased the water flow; consequently, the sediment flow has helped reduce the erosion of the southern coastline at the mouth of the branch.

The communist regime has left deep "scars" on the delta. The desire to exploit at all costs the deltaic resources has led to gigantic and ambitious projects that were disproportionate in comparison to the natural and fragile space represented by the delta. These projects displayed no regard whatsoever for the ecological component and for the natural balance, the only goal being economic development. Nevertheless, the natural balance preservation problems raised by delta resources exploitation were clearly noted as early as 1927 by Grigore Antipa in his *Report on the cultivation of the swampy areas of Romania*[5], mentioned by Bethmont, 1975.

Despite the financial investments made in deltaic resources exploitation during the communist regime, many of these developments failed, and others were progressively abandoned in the last years of the communist regime and especially after the fall of the regime. Given these facts, Bethmont's question (1975) is still very much current: "How could we exploit the wealth of the delta without making its fragility show?"

5. Ecosystem Alteration and Restoration in the Danube Delta Biosphere Reserve

In the early 1990s, after the fall of the communist regime and after the construction of various fish farming and agricultural development works as well as reed exploitation and branch shortcutting to facilitate navigation, 97 400 ha, i.e., 26.7%

[5] According to him, "the potential of each section of the floodable area should be enhanced by devoting it to the production for which nature itself created it, thus achieving its productivity and profitability peak; the development system should also take into consideration that the works performed for this purpose should not alter the natural balance and trigger disastrous consequences."

of the surface area of the delta, were excluded from the natural delta circuit. The ecosystems were completely upset, and the deltaic system was disrupted. The excessive exploitation of the deltaic natural resources in this region has resulted in the disappearance of reproductive areas used by the native fish and other animal species (twenty bird species have disappeared) and in the clogging of the natural channels. The building of oversized canals (e.g., the Mila 35 Canal and the Crisan-Caraorman Canal) has trivialized and transformed the deltaic landscape. This ecosystem disruption and the need to protect an exceptional biodiversity – the heterogeneous mixture of habitats developed in the delta shelters a large community of plants and animals, the number of which is estimated to be approximately 5 380 – and restore these ecosystems were arguments in favor of declaring the Danube Delta a Biosphere Reserve. Thus, in 1990, the Danube Delta, including the Razim-Sinoe lagoons area, was declared a Biosphere Reserve (by the Government Decision no. 983, article 5) with an independent management and scientific council.

That same year, i.e., in 1990, the Danube Delta (more precisely, its waterfowl habitat) was recognized as a Wetland of International Importance as defined by the Ramsar Convention of 1971; consequently, the Danube Delta has been included on UNESCO's list of World Heritage Sites. Also under the aegis of UNESCO, the Danube Delta was included in the MAB (*Man and Biosphere*) Programme in 1991. Finally, the law of 1993 (Law n°82 of December 7) and the Government Decision n°248 of 1994 stipulate the reserve law, its operation, scientific council, management board, and security and control team. This law was amended and adapted by Law no. 136/2011. According to these legislative documents, the Danube Delta Reserve is an ecological area of national and international importance. This area includes the deltaic space, the Murighiol Plopu salt marshes, the Razim Sinoe lagoon system, the Isaccea-Tulcea section and the Black Sea coastline from the Chilia Branch to Cap Midia, also including the territorial waters.

Within this perimeter, the Danube Delta shelters a large number of species belonging to a large number of systematic units. Moreover, the Danube Delta stands out due to its very high density of rare species or species that do not exist elsewhere on the continent. The protection of fauna, more precisely of birds, and also of forests became a must approximately 80 years ago, after the First World War. After 1930, there were two natural reserves: Letea Natural Park (1930) and Rosca-Buhaiova-Hrescica Area (1940). In 1950, thanks to the creation of the Commission for Natural Monuments by the Romanian Academy, the number of natural reserves increased to 6 (3 bird reserves, one forest reserve and two bird and forest reserves). At that time, the overall surface area of the reserves was 41 046 ha.

Whereas other protected areas (national parks, natural monuments, strict natural reserves, etc.) enjoy strict protection, the Danube Delta Biosphere Reserve has several objectives. These are the preservation of the ecosystems (flora and fauna), the stimulation of traditional economic activities that are not harmful or are minimally harmful to the ecosystems, and the information and education of the population about the scientific importance of the existing ecosystems and the importance of their preservation. This concept of a reserve should be integrated as a deltaic space management tool meant to harmonize the traditional economic activities of the local population with the requirements of nature preservation. According to this concept, three types of zones were defined in the Danube Delta Biosphere Reserve (Figure 11).

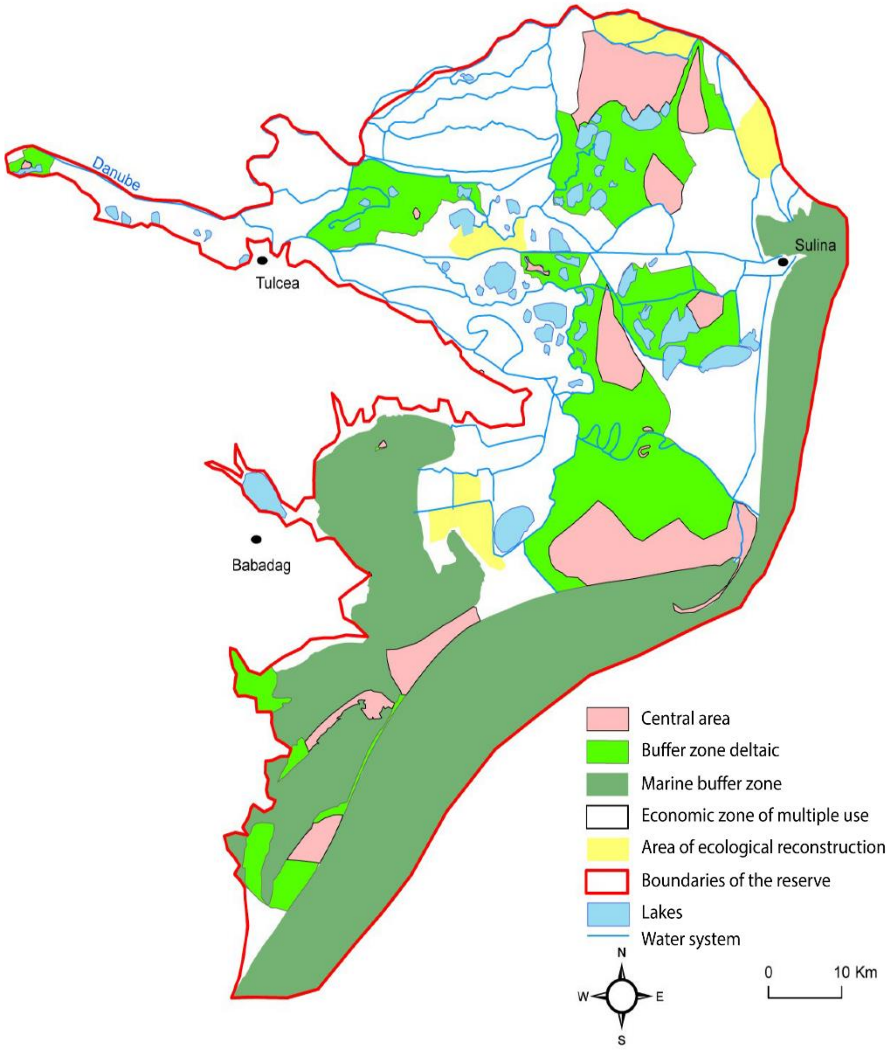

Figure 11. Danube Delta Biosphere Reserve zoning: protected zones; buffer zones: deltaic and marine; the economic zones.

The strictly protected zones have an overall surface area of 506 km² (i.e., 8.7% of the total surface area). These zones include 20 reserves in which any economic activity is forbidden. Human access is permitted only for scientific research or environmental monitoring purposes. Buffer zones (2 233 km^2, i.e., 38.5% of the total surface area) are generally defined around the strictly protected zones. Certain traditional natural resources exploitation activities are allowed in the buffer zones. These zones are intended to reduce anthropogenic pressure and to ensure a smooth transition to the economic zones. The economic zones (3 061 km² or 306 100 ha, i.e., 52.8% of the area of the reserve) include floodable land, land protected by dykes for agricultural, fishery or forestry use, and localities. All economic activities are allowed in these zones; however, certain restrictions imposed by the ARBDD[6] may apply. Whereas all the zones which were previously altered are included in the reserve, these "altered" zones are not on UNESCO's list of World Heritage Sites; therefore, its surface area is only 312 440 ha.

6. Site Restoration in the Danube Delta

In the last decades of the 20th century, the Danube Delta has suffered due to anthropogenic interventions that led to dramatic changes in some areas. These interventions were the impoundment of large areas for intensive agricultural, fishery and forestry use, which led to dramatic alterations and changes in water balance. These interventions also affected natural processes, the ecological balance and the specific ecological functions of wetlands and led to alteration or even additional specific loss of wetland habitats. When work was halted in 1990, the impounded areas occupied an area of 97 408 ha (22% of the total area of 482 592 ha). Studies for the rehabilitation/re-vegetation of this area were initiated immediately after the Danube Delta was declared a Biosphere Reserve in1990.

Within the reserve, there are ecological reconstruction zones, that is, areas in which the ARBDD has initiated ecological balance restoration projects using adequate technical means. This ecological reconstruction policy concerns all the previously dammed areas (97 408 ha, i.e., 27.6% of the current area of the delta) that are devoted to agricultural and fish farming developments or to reed exploitation. Considering that the Danube Delta includes 30 types of ecosystems that are highly dependent on the oscillation of river levels, the main objective of this ecological recovery is to restore the natural hydrological circuit of the economically developed areas. A solution to these efforts of reconnection to the hydrological regime of the delta was suggested in 1994; it consisted of digging holes in the dykes, thereby allowing the water to flow freely in these dammed areas. Other types of ecological restoration development include the calibration and closing of canals if the water flows directly towards the lakes without being filtered by the reeds.

So far, 328 km of canals have undergone ecological reconstruction development as well as drainage and unclogging, whereas 15 712 ha have been reconstructed to

[6] Management of the Danube Delta Biosphere Reserve.

be environmentally friendly. The ecological reconstruction developments were conducted in Popina (southern part), Babina, Cernovca, Fortuna and Holbina-Dunavat (Figure 12). Other types of developments (on the canals) may be found in Matiţa-Merhei, Magearu-Cardon, Gorgova-Uzlina, Şontea-Fortuna, Dunavăţ-Dranov, Roşu-Puiu and Somova-Parcheş. The ecological progress made after these redevelopments includes the establishment of new bird and animal habitats, widening of the fish and waterfowl reproduction areas, increased hydrological flow and storage capacity of water, and increased sediment retention.

After the political changes in Romania in the early 90's, the first proposed project in the Danube Delta Biosphere Reserve was Babina. The goal of this project was to switch from an intensively used, unspecified area to a state close to that of nature. Thus, in spring 1994, abandoned agricultural land in Babina in the northeastern Danube Delta has been reconnected to the natural regime of flooding of the Danube (Figure 12). A monitoring program has also been developed and implemented to answer major questions raised by the recovery process and to check the ecological success of the reconstruction work.

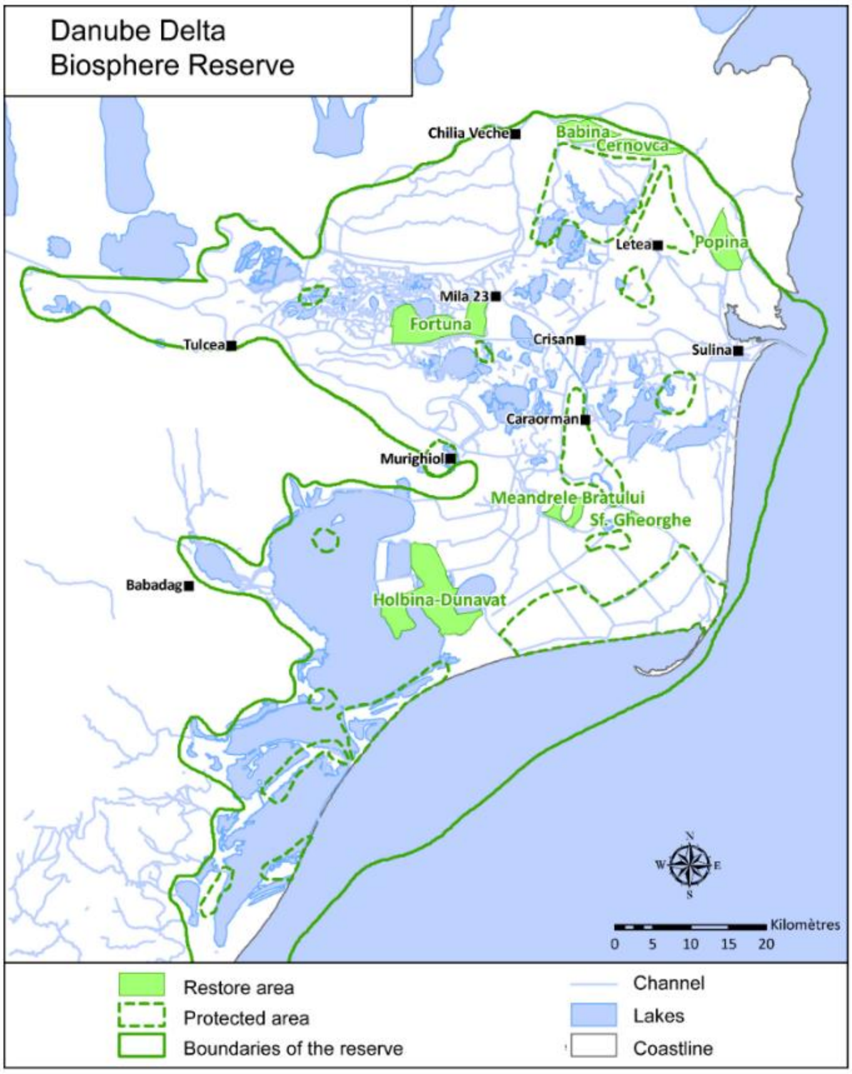

Figure 12. Ecological Restoration Areas: The ecological reconstruction developments were conducted in Popina (southern part), Babina, Cernovca, Fortuna and Holbina-Dunavat.

After the commissioning of the Babina and Cernovca dykes (1994) and after the recovery of the floodability index, these two polders saw the emergence of different plant associations that depended on the Danube level fluctuations and on land morphometrics. The following habitats were restored in the Babina Polder: aquatic habitats, low and midland levee habitats and land habitats (high levees). Aquatic habitats are represented by hydrophilic species that are also found in other natural areas of the delta. These include *Hydrocharismorsus ranae*, *Lemna minor*, *Lemnatriscula*, *Nymphea alba*, *Salvinia natans*, etc. The low and midland levee habitats are represented by floodable land during major floods. Various hydrophilic species such as *Carex riparia*, *Carex acutiformis*, *Menthe aquatica*, and *Lycopus europaeus* are left behind by the floods on the midland levees located in the middle and in the eastern part of the polder. These species are subsequently replaced by the meso-hydrophilic species *Tanacetum vulgare*, *Atriplex tatarica*, *Puccinelia limosa*, and *Tamarix ramosissima*. Halophile species such as *Astertripolium* also grow on these types of levees. Low-levee vegetation is represented by hydrophilic species where *Phragmites australis* predominates; however, since 1996 this has been replaced by *Thypa angustifolia*. High levees have similar vegetation, and this has not changed after site restoration. Mixtures of *Hordeum hystrix*, *Cynodon dactylon*, *Atriplex tatarica*, *Torilis arvensis*, *Lotus tenuis*, *Verbascum blattaria*, *Artemisia annua*, and *Lactuca tatarica* grow on this type of levee. These species provide pastures for animals.

An analysis of the ecological characteristics of the plant species identified on the polders after their restoration was conducted. Specific biodiversity and remarkable hydrophilic species diversity were noted.

7. Plant Cover Estimation in the Restored Sites in the Danube Delta: A Remote-Sensing Approach

7.1 Remote sensing and restoring wetland habitats

Wetland habitat is being restored throughout the world (Zedler & Kercher, 2005); however, achieving conservation goals and objectives requires knowledge of vegetation composition, structure, and change over time with respect to attributes such as percent cover, biomass, and plant diversity (Phinn et *al*. 1999). Therefore, there is a need to further develop, refine, and disseminate site- and landscape-level monitoring methods (Simenstad et *al*., 2006). Having developed criteria for selecting wetland sites to be restored or enhanced, wetland managers must prioritize the sites based on ecological and economic considerations (Klemas, 2013). Remote sensing techniques can provide a cost-effective means for selecting restoration sites and observing their progress over time.

Remote sensing involves the acquisition of information about the Earth's surface at a remote distance, usually by airplane or satellite (Jensen 2000). It offers tools to map, measure, model, and evaluate wetland restoration efforts in a cost-effective manner. The use of this technology in the ecological sciences is rapidly increasing because ecosystems such as wetlands can be monitored at various spatial and temporal scales (Jensen et *al*. 1995; Guo & Psuty 1997; Michener & Houhoulis 1997; Apan et *al*. 2002; Heinl et *al*. 2006; Papa et *al*. 2006; Niculescu et *al*., 2016).

Despite the increasing use of remote sensing for wetland inventory and monitoring, there has been limited use of this technology in the restoration of wetlands (Phinn et al. 1999; Hinkle & Mitsch 2005). Remote sensing is ideal for monitoring restored wetlands because it provides a high spatial and temporal intensity of measurements in relatively inaccessible and sensitive sites without the potential invasiveness that traditional field methods present to delicate habitat conditions, bird-nesting territories, and endangered species habitat (Schuman and Ambrose, 2003). In an ideal situation, remotely sensed images are acquired when decisions can be made about imagery specifications and field data collection that will make change detection accurate and applicable to the monitoring of a restoring wetland.

Recent advancements in imaging science have provided finer spatial, spectral, and temporal resolution as well as reduced price. In addition, non-optical data sources such as radar data (e.g., SAR, RADAR) and laser altimetry (e.g., LiDAR), have been shown to add value when combined with optical remote sensing data (Ramsey et al. 1998; Rosso et al. 2005b; Niculescu et *al*., 2016). Change detection is an important tool for wetland restoration monitoring because it provides measurements of incremental changes that can be used for inventory and benchmark purposes; knowledge of these changes can then be integrated with adaptive management plans and used to target specific restoration goals (Tuxen et *al*., 2008).

The success of restoration, however, is difficult to assess. The degree of success for many of these restoration sites is still being debated, especially since there is no full agreement on criteria used to measure success. The creation, enhancement, or restoration of coastal habitats requires much time and constant attention (Klemas, 2013). Remote sensing offers accurate automated methods for detecting change in restored wetlands. Vegetation change detection is a powerful indicator of restoration success. The restoration projects use vegetative cover as an important indicator of restoration success.

Synthetic aperture radar (SAR) technology provides the increased spatial resolution that is necessary in regional wetland mapping, and SAR data have been used extensively for this objective (Bourgeau-Chavez et al., 2005; Lang and McCarty, 2008; Novo et al., 2002). Radar has the capability of penetrating the plant cover canopy and detecting submerged sectors and soil surface moisture. Although the spatial resolution of radar images does not allow thorough and detailed habitat mapping, these images are useful for mapping wetland vegetation. The radar polarimetry and polarimetric parameters contribute significantly to the improvement of vegetation identification based on polarization channels. Multipolarization and multi-frequency radar devices are also used for the classification of wetland vegetation depending on their wavelengths, polarizations and backscattering mechanisms and can be used to estimate the density and size of the vegetation. Microwave radiation polarization, like radar beam incidence angle and wave frequency, has long been acknowledged as an important parameter for object recognition and understanding object features. Access to the scattering matrix permits several analytical approaches and hence various ways of assessing the potential of multi-polarized radar images. One approach consists of synthesizing pixel-based signal strength, which should have been measured at the same frequency for any polarization configuration (linear and/or circular) (Niculescu et *al*., 2015). The sensitivity of microwave energy to water and its ability to penetrate vegetative canopies makes SAR ideal for the detection of the hydrologic features under vegetation.

SAR image time series such as those provided by the Sentinel-1 satellite allow significant improvements in vegetation classification. The key advantage of satellite-borne SAR imaging is its independence of cloud cover, and because it is an active sensing system, its independence of sun-induced reflection. Consequently, SAR imagery has become an important tool for distinguishing different vegetation classes. Recently, polarimetric SAR images have been analyzed using decomposition theorems such as alpha/entropy decomposition, which increases the accuracy of vegetation analysis from microwave data. However, there is a wide choice of remote-sensing satellites, radar, and optical. Whereas optical satellites usually operate in one imaging mode, radar satellites can be programmed to work indifferent configurations. The user must choose the polarization configuration, the incidence angle, and the spatial resolution associated with the chosen imaging mode. Combined approaches of using optical and microwave images can improve the vegetation analysis.

Airborne laser instruments such as LiDAR represent innovative tools for management applications, including flood zone delineation, monitoring beach nourishment projects, and mapping vegetation (Niculescu et al., 2016) and changes along sandy coasts and shallow benthic environments due to storms or long-term sedimentary processes (Klemas, 2013). Identifying potential restoration sites and prioritizing them using ecological and economic criteria is by no means a simple task (Russell, Hawkins, and O'Neill, 2004; Thayer, 1992; White and Fennessy, 2005). The combined use of LIDAR, radar, and multispectral imagery can improve the accuracy of monitoring vegetation species discrimination and provide a better understanding of the topography/bathymetry and hydrologic conditions.

7.2 Dataset

We used the following satellite images in this study: 20 Sentinel-1 images acquired between 9.10.2014 and 01.04.2016 (table 2) and one Sentinel-2 image acquired on 28.04.2016 in the restored areas in the northern part of the delta (Babina and Cernovca). The Sentinel-1 data were acquired in a time series that covered the entire growth season of 2015 and part of 2016. This enabled us to determine the influence of the time dimension and of the polarimetric dimension (VV and VH polarization are available) on the characterization and classification of the vegetation in the restored delta areas.

Date	Incidence angle	Orbit
09-10-2014	38.055	Ascending
02-11-2014	38.786	Descending
26-11-2014	38.653	Descending

13-01-2015	39.215	Ascending
26-03-2015	39.856	Ascending
07-04-2015	38.569	Ascending
01-05-2015	38.421	Descending
13-05-2015	39.654	Descending
30-06-2015	39.478	Ascending
05-08-2015	38.665	Descending
17-08-2015	37.789	Descending
29-08-2015	38.669	Ascending
10-09-2015	39.285	Descending
22-09-2015	39.456	Ascending
09-11-2015	38.721	Descending
03-12-2015	38.451	Ascending
27-12-2015	39.885	Ascending
20-01-2016	38.411	Descending
13-02-2016	39.662	Ascending
01-04-2016	39.453	Ascending

Table 2: Sentinel-1 imagery used in this study

Since it was first launched in April 2014, the Sentinel-1 satellite has allowed specialists to monitor the earth's surface day and night regardless of weather conditions and has transmitted high-resolution space images free of charge. The Sentinel 1 SAR mission is part of the Copernicus Programme – European Earth Observation Programme, which was previously called GMES (Global Monitoring for Environment and Security), of the European Space Agency. Placed on an orbit at an altitude of 693 km, Sentinel-1 operates in four data collection modes: the StripMap (SM) mode, the Interferometric Wide swath (IW) mode, the Extra-Wide swath (EW) mode and the Wave (WV) mode. Each mode provides different products with respect to spatial resolution and imaging swath. Sentinel-1 images are captured in C band (5.5 cm), and they may exhibit simple HH or VV polarization or double HH+HV or VH +VV polarization. The data used in our research were collected in the IW mode. This mode includes three sub-swaths, namely IW1, IW2 and IW3, which correspond to cyclical antenna deviations. This mode provides GRD (Ground Range Multilook Detected) and SLC (Single Look Complex) images made up of three IW (MDA, 2011). The GRD images are Multilook images (five looks for the IW mode) with less speckle noise and coarser space resolution. Although the SLC products have finer resolution, it is difficult to use them directly due to the phase information, which seems useless as it prevents extraction of additional information in certain cases.

GRD image calibration is vital for viewing the maximum amount of information on an image. In our research, the σ0 value is extracted using Calibration Tools of the OrfeoToolbox software, which provides us with the backscattering coefficient of the area. These values depend on the targets illuminated by the beam, on ground roughness and moisture and, in the end, on the vegetation density.

Sentinel-2A is the second satellite of Europe's Copernicus Programme, following the Sentinel-1A radar satellite launched last year. In partnership with the European Commission and within the frame of the Global Monitoring for Environment and Security (GMES) program, the European Space Agency (ESA) is developing the Sentinel-2 optical imaging mission, which is devoted to the operational monitoring of land and coastal areas. Sentinel-2 is the operational mission devoted to the observation of continental surfaces in decametric resolution. The Sentinel-2 mission ensures a systematic full land cover with 10-day repetitiveness by a single satellite and 5-day repetitiveness by two satellites. Sentinel-2 has 13 spectral bands, 3 of which are in the near infrared (SWIR). These images have a 290-km-wide field of view and 10-m, 20-m or 60-m resolution depending on the spectral bands. The Sentinel-2 mission is a land and coastal areas monitoring constellation of two satellites (Sentinel-2A, which was launched on 23 June 2015, and Sentinel-2B, which will follow in the second half of 2016) that provide high-resolution optical imagery and continuity for the current SPOT and Landsat missions. The mission will provide global coverage of the Earth's land surface every 10 days with one satellite and every 5 days with 2 satellites, making the data of great use in ongoing studies. Sentinel-2 delivers high-resolution optical images for land monitoring, emergency response and security services. The satellite carries a multispectral imager with a swath of 290 km. The imager provides a versatile set of 13 spectral bands spanning from the visible and near infrared to the shortwave infrared, featuring four spectral bands at 10-m, six bands at 20-m and three bands at 60-m spatial resolution. The imager's 13 spectral bands, from the visible and the near infrared to the shortwave infrared at different spatial resolutions, take land monitoring to an unprecedented level. In fact, Sentinel-2 is the first optical Earth observation mission of its type to include three bands in the 'red edge', which provides key information on the state of vegetation. The 13 spectral bands span from the visible and the near infrared to the short-wave infrared. The 4 bands at 10 m are the classical blue (490 nm), green (560 nm), red (665 nm) and near infrared (842 nm) bands dedicated to land applications. The 6 bands at 20 m include 4 narrow bands in the vegetation red edge spectral domain (705 nm, 740 nm, 775 nm and 865 nm) and 2 large SWIR bands (1610 nm and 2190 nm) dedicated to snow/ice/cloud detection and to vegetation moisture stress assessment. The 3 bands at 60 m are dedicated to atmospheric correction (443 nm for aerosols and 940 nm for water vapor) and to cirrus detection (1380 nm) (Baillarin et al., 2012).

7.3 Remote-sensing methodology

The chosen methodology is associated with multi-data radar and optical image classification methodology. We began with the preliminary processing of the radar and optical images (Figures 13 and 14 show the radar data).

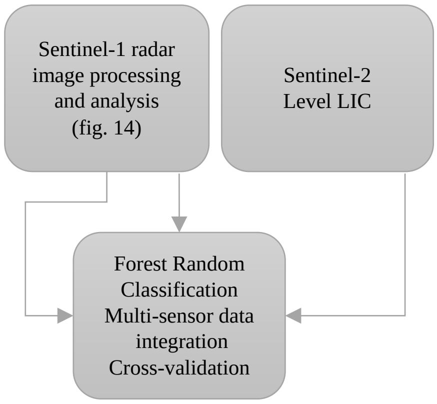

Figure 13: Data processing procedure

A typical processing sequence applied to SAR data entails radiometric calibration, speckle filtering, and orthorectification. Radar signals require pre-processing to account for geometric distortions and for differences in illumination conditions due to topography and the surface being illuminated to one side of the satellite. An additional step is needed to remove noise caused by reflections from features that are not of interest. This is called *speckle noise* and is removed by a process called *speckle filtering*. The filtering applied is filtering of the Lee type (Figure 14). Adaptive filters use local statistics to filter the data and so reduce image speckle and, in some cases, preserve or enhance edges and other features. At the same time, the backscattering coefficient was analyzed for the two different polarizations depending on a set of parameters related, on the one hand, to the RSO characteristics (acquisition frequency, polarization and geometry) and, on the other hand, to the attributes of the target (geometric structure, dielectric constant, biomass, etc.). The backscattering coefficient is usually expressed in decibels (dB), yielding a normalized value comparing the observed power to the rated power for an equivalent 1-m^2 surface and corresponding to the distance to the ground. The backscattering coefficient is also very much influenced by factors related to the sensor configuration and collection geometry.

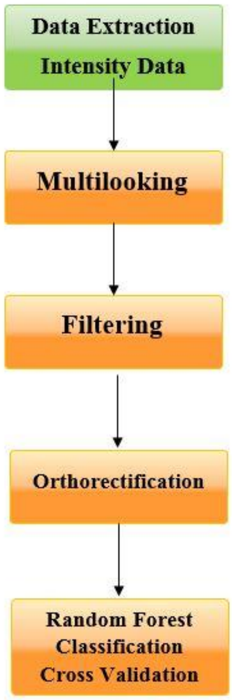

Figure 14: Radar data processing procedure

The optical image (Sentinel-2) was already orthorectified in the UTM 35N cartographic system by ESA (level 1C). The geometric correction of image data is an important prerequisite that must be performed prior to using images in geographic information systems (GIS) and other image-processing programs. To process the data with other data (radar) or maps in a GIS, all the data must be based on the same reference system. Using a combination of different sensors, we resampled the data to the smallest pixel size between optical and radar. All the datasets were orthorectified, resampled to a 10-m pixel size and separately classified.

We then performed synthetic Random Forest classifications, first for all the Sentinel-1 radar data and then using combinations of the Sentinel-2 image. The supervised classifier used is the Random Forest algorithm, which is available in OrfeoToolbox (version 5.0) free software. Random Forests offers high-quality mapping of different vegetation types with much faster computation compared to other state-of-the-art classifiers such as, for instance, Support Vector Machines with Gaussian kernels (Inglada et *al*., 2016). Random Forest is an ensemble learning technique and builds upon multiple decision trees. Each decision tree is built using a subset of the original training data and is evaluated based on the remaining training features. New objects are classified as the class that is predicted by the most trees.

According to Rodriguez-Galiano et *al*., 2012, the classifier has three main advantages for land cover classifications from remote-sensing images: (i) it reaches higher accuracies than other machine-learning classifiers; (ii) it has the ability to measure the importance level of the input images; (iii) it makes no assumptions about the distributions of the input images (cited by Hütt et *al*., 2016). We use the following parameters for the Random Forest algorithm: 100 trees, maximum depth of the tree 25 and minimum number of samples in each node 25.

The final stage of image processing relates to the integration of several images from two satellites (Sentinel-1 and Sentinel-2), which have different spatial resolutions. Image integration is a method for combining information from various sources. The combined analysis of optical and microwave imagery uses the advantages of both systems for vegetation classification.

7.4 Field Observation and Validation of Results

Another method is field observation and validation of results. Field observations are vital in remote sensing. In our research, the data collection stage prior to validation of the results of supervised classifications includes two categories of surveying methods, random (probabilistic) methods and empirical (non-random) methods. The survey was based on the satellite imaging document. Point sampling was used during this data processing stage. For each class, 1000 training points and 1000 control points (not the same points) were randomly chosen. This survey determines whether an observation unit belongs to a sample by random draw. In this case, the probability law is known. The random draw is stratified starting from all the homogeneous thematic areas. The stratification was initially performed prior to the field investigation phase. This first stage stratification is a morphological stratification that relies on textural homogeneity, backscattering and thematic homogenization criteria. As concerns field observations, the ground surveys (twenty floristic surveys per thematic class) carried out in the restored delta areas allowed us to determine the vegetation typology in the surveyed area. Vegetation description is physiognomic and includes land cover rate estimation. Depending on the size of the homogeneous area, the size of the observation unit is more or less significant. The vegetation structure and type were measured at each point within a 100-m radius of the observer. Some floristic information was also gathered, including a list of species classified by physiognomic layers (trees, shrubs, and grasses).

The results of the evaluation are summarized in a confusion matrix. Based on the confusion matrix, statistical accuracy parameters are calculated. One is the overall accuracy, which counts pixels that are correctly classified in the reference divided by all pixels that are taken for reference. This procedure is used for both optical and microwave image classification.

7.5 Remote sensing and restoration areas in the Danube Delta

The results of this study relate to combinations of data from different satellite sensors (Sentinel-1 time series, Sentinel-2) that are used to improve the accuracy of recognition and mapping of major vegetation classes in the restoring areas in the

Danube Delta. First, the data from each sensor are classified and analyzed. The results show quite good classification performance (87.5% mean accuracy for Sentinel-2; 95.7% for the Sentinel-1 time series) in this first step. The combination of the Sentinel-2 time series and optical data from Sentinel-2 improved the performance of the classification (97.1%) (Figure 16).

The vegetation types were labeled according to 10 classes (figures classifications). These classifications allowed us to distinguish several classes of reeds in the 'large marsh vegetation' class (reed vegetation on salinized soils, pure reed vegetation, and reed vegetation on open plaur (floating vegetation called *plaur* (floating reed bed) is an association of reeds and other wetland plants that grow on a one-meter thick cover made up of roots, soil and various organic materials) and two classes of reed vegetation on compact plaur (one class with cut reeds).

The classification accuracy of the Sentinel-2 image (Figure 15) was estimated to be 87.5%, which was inferior to that of the time series from the radar data provided by Sentinel-1. The Sentinel-1 images time series classifications (95.7% mean accuracy) display very good accuracy.

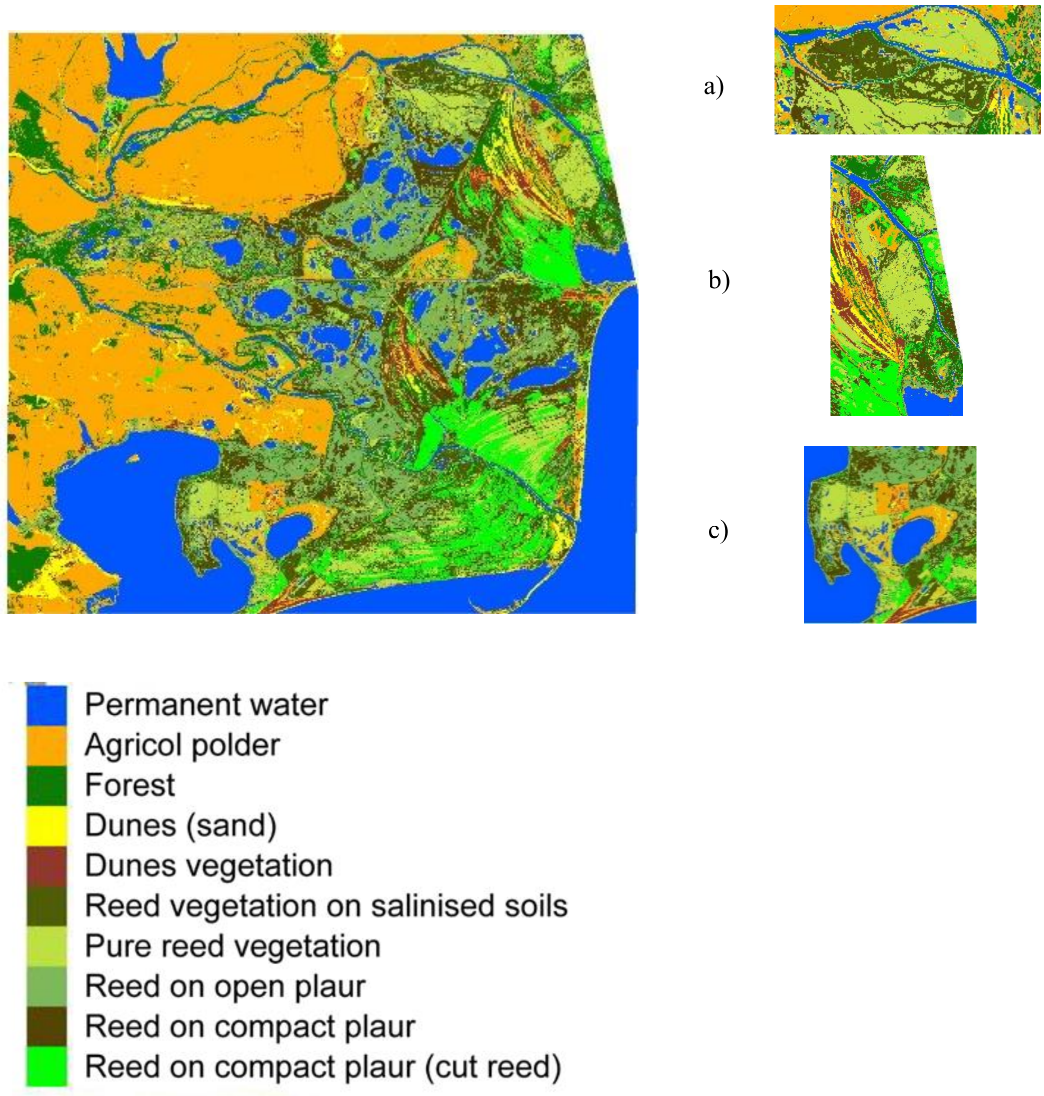

Figure 15: Random Forest classification in 10 classes vegetation: Optical image Sentinel-2. 5 classes of reed vegetation with some confusion between these classes. The restored areas: a) Babina-Cernovca; b) Popina; c) Dranov-Holbina.

The classification precision analysis per class proves that the Sentinel-2 images allow the identification of all 10 classes of vegetation considered in this study. The following classes exhibit satisfactory accuracy for some of the restoring areas: reed vegetation on salinized soils (81.4%), pure reed vegetation (76.9%), reed vegetation on open plaur (87.3%). On the other hand, the class ‘reed on compact plaur’ exhibited lower performance in the mapping results, yielding an accuracy of 59.7%.

Class	**Sentinel-2 Per cent accuracy**
1	100.0
2	91.5
3	90.0
4	98.4
5	94.4
6	81.4
7	76.9
8	87.3
9	59.7
10	96.4
Mean	**87.576**

Table 3**:** Performance of the classification by class and all classes of the Sentinel-2

By integrating the Sentinel-1 time series with optical images such as Sentinel-2, the quality of the habitat maps of the restoring areas in the Danube Delta can be considerably improved (Figure 16).

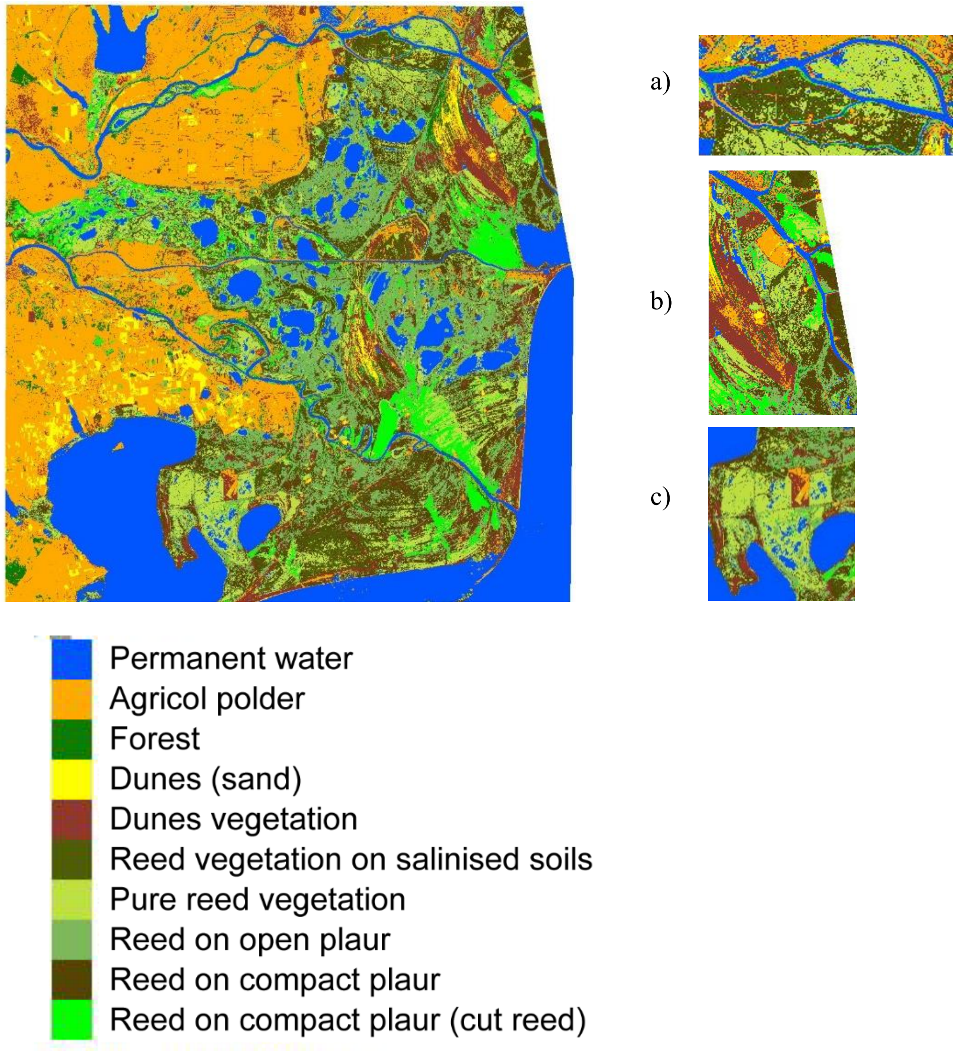

Figure 16: Multi-sensor data integration Sentinel-1 radar time series and Sentinel-2 optical sensor.5 classes of reed vegetation and less confusion between these classes. The restored areas: a) Babina-Cernovca; b) Popina; c) Dranov-Holbina.

Data integration between the Sentinel-1 and Sentinel-2 images provides classification with an overall accuracy of 97.1% and very good class accuracies ranging from

90.3% to 95.8%. The classes ‘reed vegetation on salinized soils’ (97.1%), ‘pure reed vegetation’ (

91.1%), ‘reed on open plaur’ (97.9%), and ‘reed on compact plaur’ (cut reed) (99.9%) were well mapped and show good accuracy (table 4 and Figure 17).

Class	Sentinel-1 Per cent accuracy	Radar+optical Per cent accuracy
1	99.5	99.8
2	95.1	98.3
3	96.4	98.1
4	94.5	99.6
5	96.8	99.5
6	96.8	97.1
7	92.1	91.1
8	96.7	97.9
9	91.5	90.3
10	99.4	99.9
Mean	**95.87**	**97.151**

Table 4: Performance of the classification by class and all classes of multi-sensors and time series of Sentinel-1

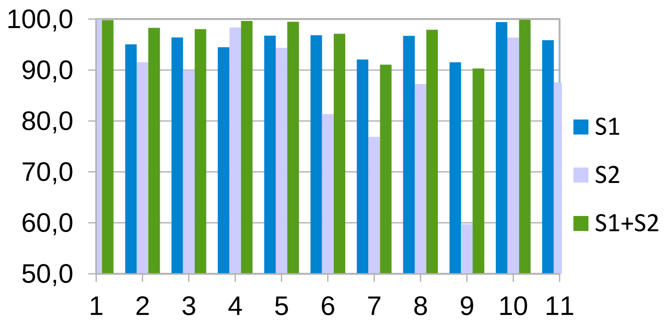

Figure 17: Performance for the multi-sensor and time series classification by class (per cent accuracy) (S1=radar sensor time series Sentinel-1, S2=optical sensor Sentinel-2 and S1+S2=multi-sensor data integration)

The mapping accuracies were summarized using confusion matrices and statistics including user, producer and overall accuracy and Cohen's K (Figure 18). Classification accuracy was assessed using global and Kappa indices. Very good Kappa indices were obtained; for the optical data, the Kappa index was 0.86, and for the multi-sensor data integration, the Kappa index was 0.96. The classification accuracy was estimated using cross-validation and by calculating the percentage of correctly classified pixels on the resulting maps. These present the reference class labels in rows and the labels predicted by the classifier in columns. The results are expressed in percentages with respect to the reference labels, and therefore, values in the diagonal represent Producers Accuracy.

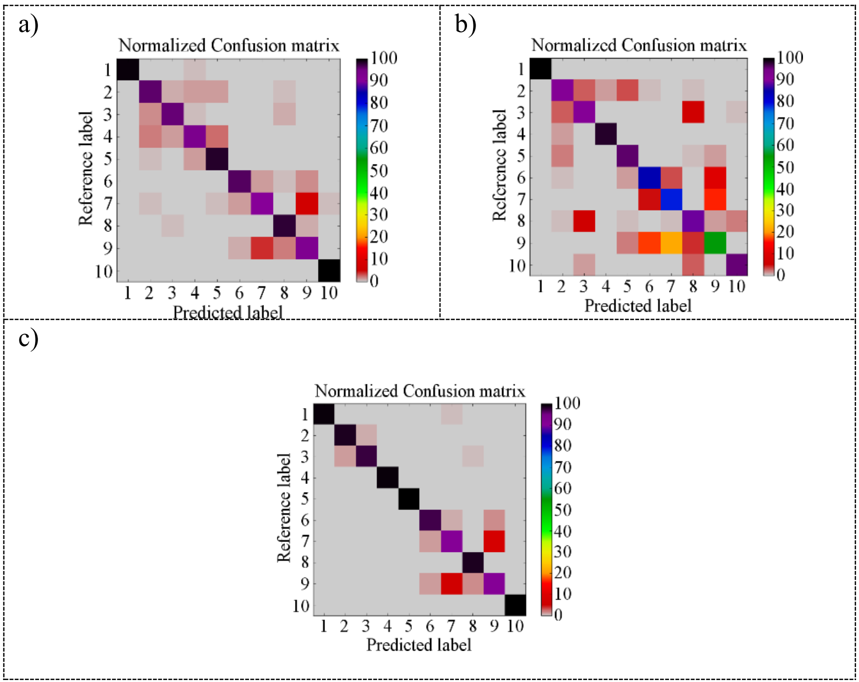

Figure 18: Confusion Matrix of Random Forest classifications: a) Sentinel-1 time series; b) optical data Sentinel-2; c) Multi-sensor data integration. Very good Producers Accuracy values for the confusion matrix of Sentinel-1 radar: most classes show values ranging from 90.01% to 99.72%. The confusion matrix of optical data with many confusions of reed class. The confusion matrix of the multi-sensor data integration: the Producers Accuracy rates were higher than 90%, i.e. ranging from 90.4 to 99.91%.

Figure 18 shows the confusion matrix for the optical data. The matrix reveals many confusions of reed classes involving different forms (reed on salinized soils, pure reed, reed on compact plaur). The most important confusions concern the various reed classes that characterize the habitats in the restored areas. ‘Reed on compact plaur’ has a Producers Accuracy of 55.1%, with confusions with the ‘pure reed vegetation’ class (16.26%) and the ‘reed vegetation on salinized soils’ class (10.42%). Other confusions concern the ‘pure reed vegetation’ class, which displays a Producers Accuracy of 78.65%. The most important confusion in this class, 21.50%, is represented by the ‘reed on compact plaur’ class. Thu, even when optical data are used, the distinction between the plant formations of these wetlands is not always easy. Prior research has revealed that when optical imaging is used there is spectral confusion between wet and dry environments and also between various types of wetlands. Marsh and swamp identification in the spring usually causes fewer problems than identification of wetlands with drier water regimes, such as peat bogs or swamps with considerable foliar biomass (Ozesmi and Bauer, 2002).

The confusion matrix of the classification resulting from the Sentinel-1 time series processing reveals very good Producers Accuracy values; most classes show values ranging from 90.01% to 99.72%. The most substantial confusions concern the ‘pure reed vegetation class’, with a Producers Accuracy of 90.01%. This class is mixed with the ‘reed on compact plaur’ class (4.21%) and with the ‘reed vegetation on salinized soils’ class (1.26%). Radar data provide information especially on plant physiognomies. This analysis supplies information on polarimetric data in relation to the geometric characteristics of the physiognomies of the plants growing in the restored areas of the delta and enables us to draw conclusions about ways to distinguish among the various plant physiognomies.

Finally, the confusion matrix of the multi-sensor data integration revealed excellent classification results when the Producers Accuracy rates were higher than 90%, i.e., between 90.4 and 99.91%. The low confusion values shown by this matrix concern the two classes for which we also read confusions in the previous matrices: reed on compact plaur and pure reed vegetation.

7.6 Temporal Intensity Radar Data Signature

Our analysis will primarily address the different reed classes (Figures 19 and 20).

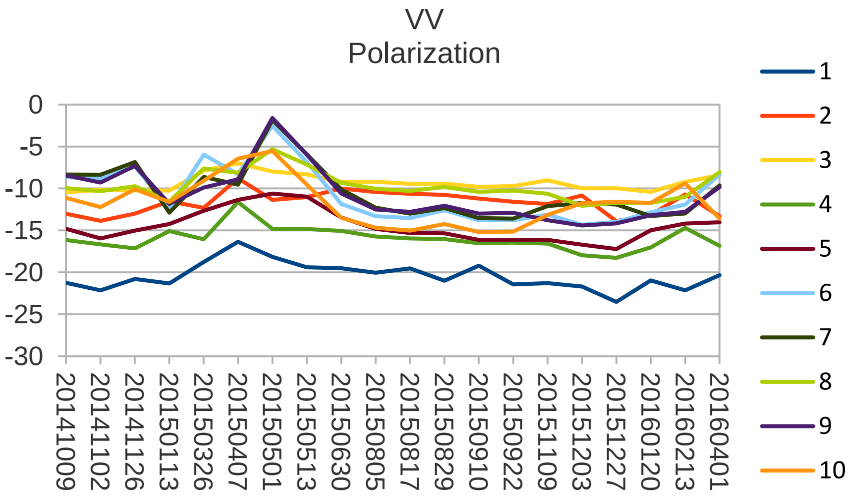

Figure 19: Temporal Intensity Radar Data Signature. Polarization VV

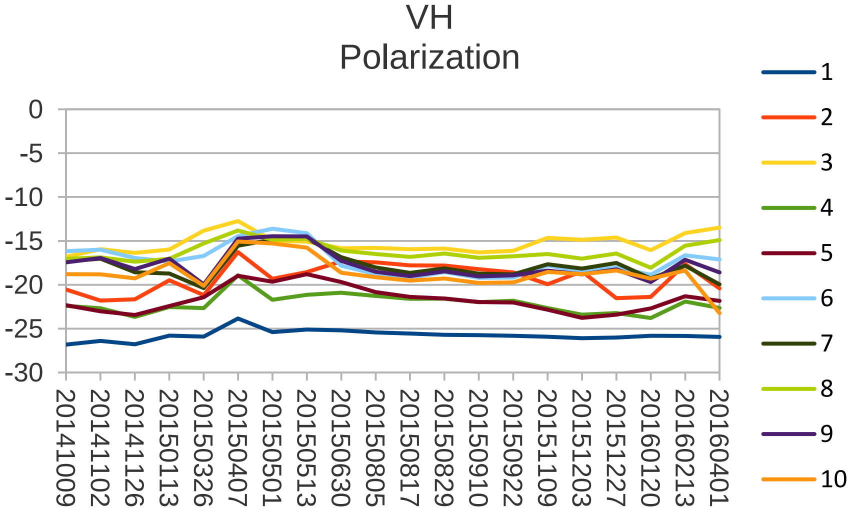

Figure 20: Temporal Intensity Radar Data Signature. Polarization VH

On average, the temporal variation is similar whatever the polarization, VV or VH; from 2014 November to 2015 January, the radiometry is not really changing because at this period the landscape is not changing very much. In March in early spring, the different reed sites are characterized by surface backscattering with poor symmetric backscattering values. This surface backscattering is supported by the low intensity values of the VV polarization channel. The polarization channel values increase between late April and early June, indicating a transition from surface backscattering to dipolar backscattering. Between early June and late September, this dominant dipolar backscattering becomes almost representative of the total backscattering. In April and May, the backscattering values of different reed sites increase significantly due to the combined action of mature biomass and denser and taller vegetation. The decrease in the water level from ≈2 m to ≈1 m between July and August-September also accounts for this backscattering decrease. Signal saturation in band C and the difficult substrate access, due to water drainage at most of the sites, led to a decrease in all the intensity parameters. The main backscattering source thus shifts towards the upper part of the canopy, where the large, raised reed leaves enhance rather than reduce signal backscattering. An important observation concerns the temporal evolution of backscattering. We noted that the backscattering peak is reached when consistent backscattering mechanisms are in place (in May/June), correlating with the increased aerial biomass.

The foregoing observations show that there is a transition from surface backscattering in early spring, during which the first plant growth phase occurs (May-June), to dipolar or double-bounce non-dominant backscattering. This mechanism continues to be dominant during the second phase (July-August) up to plant maturity; it then turns into volume backscattering during the senescence phase.

On VH polarization, the species of the various reed classes make up a very homogeneous group, and there are few differences between the various seasonal signatures. For these classes, the backscattered power peak is reached in May and June, when consistent backscattering mechanisms are in place and the aerial biomass reaches its peak height.

8. Conclusion

According to research conducted by the United Nations Environment Programme, 40% of the global economy depends on the proper functioning of ecosystems. In most cases, the ecosystem that needs restoring has been degraded, damaged, transformed or completely destroyed as a direct or indirect result of human actions. Ecological restoration should become a priority so as to limit the process of degradation of the environment, to contribute to the preservation of fragile habitats and of critically endangered species and to ensure the valorization of natural resources. Over time, human intervention has manifested itself in more than a quarter of the entire surface of the Danube. This intervention was brutal and has rendered ecosystem restoration very difficult. Over time, the development of fluvial-maritime navigation and of resource use policies applying to the Danube Delta (fish, agricultural, forestry, and other resources) has determined the main water system and landscape transformations in the Danube Delta.

After the fall of the communist regime, ecologic restoration actions were conducted in the delta. This ecologic reconstruction policy concerns all the dammed areas (27.6% of the current surface area of the delta) that had been previously developed for agriculture, fish farming and reed processing. Considering that the Danube Delta includes 30 types of ecosystems that are highly dependent on river level oscillation, the main objective of this ecological recovery is to restore the natural hydrological circuit of the economically developed areas. A solution to these efforts of reconnection to the hydrological regime of the delta was suggested in 1994; it consisted of digging holes in the dykes to allow the water to enter and flow freely in these dammed areas. For the observation and analysis of the restored ecosystems in these areas, we relied on state-of-the-art Sentinel-1 and Sentinel-2 radar and optical satellite imaging and remote sensing methodology. Remote sensing offers accurate automated methods for detecting change in restored wetlands. Vegetation change detection is a powerful indicator of restoration success. The restoration projects use vegetative cover as an important indicator of restoration success. Our research, which relies on several series of radar images captured especially during the growth period, enables us to improve plant formation recognition by exploiting the temporal dynamics of the various plant classes of the restored areas of the delta. Temporal analyses revealed that no single date allows satisfactory characterization of all the vegetation classes. Thus, the temporal dimension, which is represented by seasonal evolution, is an essential component if we intend to draw up a detailed inventory of the restored vegetation classes in the delta.

The synergy of a time series of radar satellite observations with the optical data and radar data can be exploited to improve monitoring and analyze the vegetation in the restoration areas of the Danube Delta. Information from different sensors may assist in the variable retrieval by limiting potential ambiguities. The temporal resolution of the optical sensor Sentinel-2 does not provide temporally frequent products of vegetation characteristics due to the cloud coverage. Application of a multi-temporal radar, multi-sensor approach to a temporal sequence of data acquired by different sensors can improve mapping and monitoring of vegetation state variables over time. By integrating the Sentinel-1 time series with optical images such as those obtained by Sentinel-2, the quality of the habitat maps of the restoring areas in the Danube Delta can be improved considerably (97.1%). Very good Kappa indices were obtained; for the time series radar, the Kappa index was 0.96, and for multi-sensor data integration the Kappa index was 0.97. The reliable Producers Accuracy and K coefficient results prove the complementarity of the two satellites for the observation, analysis and spatial representation of the deltaic plant ecosystems. The Producers Accuracy analysis by class shows that the Sentinel-2 sensor has its limits concerning the detection of similar plant classes, such as, for example, the different classes of reed. Although this sensor detects these classes, the mapping precision is not always high (on some occasions, it is approximately 55% for the ‘reed on compact plaur’ class). In contrast, the use of a Sentinel-1 time series reveals an interesting C band radar time signature in the Danube Delta ecosystem. Moreover, the combination with Sentinel-2 data resulted in considerable reduction of the observed confusions for both Sentinel-1 and Sentinel-2 with, for instance, a Producers Accuracy value of the ‘reed on compact plaur’ class of 90.46%, as well as increased accuracy for other reed classes.

As revealed by the data collected by the satellites used in our research, the plant cover of the restored areas appears to be normal and to consist of plant formations similar to those found in the natural areas of the delta. Therefore, we could conclude that plant ecosystem restoration in the Danube Delta has been successful.

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