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Land subsidence in the Friuli Venezia Giulia coastal plain, Italy: 1992–2010 results from SAR-based interferometry

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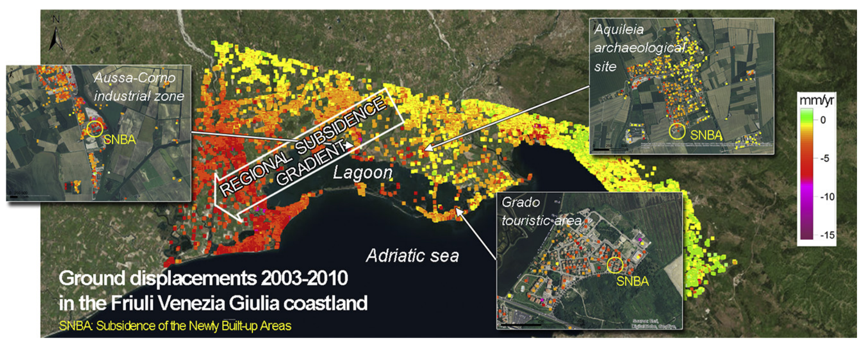
HIGHLIGHTS

- The coastland subsides from 1 to 5 mm/yr and locally more than 10 mm/yr.
- Land subsidence regional trend mainly depends on the geologic characteristics.
- Cumulative 1992-2010 land subsidence exceeds 110 mm.
- Uneven human-induced coastal subsidence is revealed at local scale.
- Newly built-up areas subside more than older urbanization.

GRAPHICAL ABSTRACT



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ABSTRACT

Land subsidence is a concern in many coastal plains worldwide, particularly in the low-lying areas already facing sea level rise due to climate change, and much still needs to be done, with respect to both mapping land subsidence and gaining a comprehensive understanding of the relevant cause-effect relationships. Land subsidence of the northern coastal plain encompassing the Friuli Venezia Giulia (FVG) region in Italy, remains, to the authors' knowledge, poorly investigated. This coastland includes low-lying agricultural and urban areas and highly valuable lagoon environments, archaeological and touristic sites, and industrial zones.

Here, we resolve land subsidence in the coastal plain between the Tagliamento River delta and the Isonzo River mouth over the period 1992–2010 using Envisat ASAR and ERS1/2 interferometric datasets. We identify a large variability of the land subsidence and a spatial gradient that ranges from less than 1 mm/year in the high southwestern plain toward the littoral to more than 5 mm/year close to the Tagliamento River delta. A comparison between the 2003–2010 and 1992–2000 sinking rates depicts quite similar behaviors of the process over the two time spans. The analysis indicates unclear correlations between ground movements and the typical driving mechanisms acting in the north Adriatic coastal plains, such as the variability of the morphological setting, the subsoil characteristics and the land use. We reason that multi-component mechanisms contribute to the observed image of the subsidence in the FVG coastland. Specifically, anthropogenic activities, e.g., groundwater exploitations, hydraulic reclamations and the development of newly built-up areas, are superposed to natural mechanisms related to the spatial variability of the subsoil characteristics, typical of transitional coastal environments.

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1. Introduction

Coastal plains, river deltas, estuaries, tidal marshes and lagoons are the environments most susceptible to the effect of land subsidence worldwide because a key determinant of their vulnerability is the extent to which the lowering of their surface elevation contributes to relative sea level rise. Therefore, understanding subsidence-induced changes in these landscapes represents a breakthrough in sustainable land use, flood mitigation and restoration plans, safeguarding of natural and cultural heritages and the safety of people that live on them (Syvitski et al., 2009; Abidin et al., 2011).

The northwestern Adriatic coast encompasses the largest Mediterranean low-lying coastlands, including deltas, estuaries, lagoons, wetlands, and farmlands, whose present landscape is the result of hundreds of years of human intervention. Anthropogenic activities and urban and industrial centers threaten these valuable transitional ecosystems and historical and archaeological sites, which are found widely throughout the northern Adriatic coast.

The coast of the Friuli Venezia Giulia (FVG) region is located in the northernmost Italian tip facing the Adriatic Sea. The coast is characterized by a Pleistocene-Holocene plain sector, including the Grado-Marano lagoon, minor wetlands, the Tagliamento River delta and the Isonzo estuary, and a carbonate steep cliff sector related to the alpine chain.

Most of the coastal plain is characterized by low-lying parts that are below sea level and covered by farmlands and minor urban centers. These features are the results of hydraulic reclamation works carried out over the past centuries to drain former wetlands and lagoons.

Therefore, the preservation of ground elevation is one of the main issues facing this area, in addition to maintaining the efficiency of the drainage systems to reduce the effects of flooding and seawater intrusion (Da Lio et al., 2015). The Grado-Marano lagoon is an extremely important wetland of significant ecological worth that is particularly fragile (Fontolan et al., 2012). The morphology of the lagoon is a result of sedimentary processes (e.g., deposition, erosion), climate change (e.g., sea level rise, storms), and human interventions and activities (e.g., coastal protections, land use). Consequently, the lagoon ecosystem depends on the mutual interaction between these forces, among which the effect of the relative sea level rise (RSLR), i.e., eustacy plus subsidence, must also be included (Carbognin and Tosi, 2002).

The study of land subsidence in the north Adriatic coastland dates back to the mid-1900s. Since then, hundreds of analyses have been performed. The Po River delta and the Veneto and Emilia Romagna coastal plains are the areas most commonly investigated, whereas the subsidence along the FVG coast remains poorly investigated. Marchesini, 2006 analyzed the displacements measured across different time spans over the period 1980–2004 along a local leveling network bounding the eastern part of the Grado-Marano lagoon and noted a general subsidence trend of approximately 2 mm/year and a local sinking rate of 3–4 mm/year. Through a comprehensive investigation of the relative sea level changes of the Italian coastlines, Antonioli et al. (2009) analyzed the ground movements of national leveling lines and noted an increasing subsidence trend from both Venice and Trieste toward the Tagliamento River with sinking values ranging from 3 to 4 mm/year in the nearby northern lagoon margin. Alfarè et al. (2014) using SAR-based interferometry and geological data to assess the subsidence in a restricted sector of the FVG coastland including the historical city of Aquileia and a small part of the Grado-Marano lagoon. The results of this study noted the significant heterogeneity of the subsidence process, which has never been assessed using leveling.

Presently, despite the high vulnerability of coasts to climate change hazards (e.g., Torresan et al., 2012) and the need to protect the great environmental, agricultural and cultural value of the FVG coastland, a comprehensive and detailed assessment of the land subsidence characterizing this area has, to the authors' knowledge, never been conducted.

Starting in 2007, the Italian Ministry of the Environment and Protection of Land and Sea, within the framework of the Special Plan of Remote Sensing of the Environment, committed to measuring surface deformation using SAR-based interferometry of all available Envisat ASAR and ERS images over Italy. However, in many cases, the interferometric products are not directly usable for quantifying absolute ground velocities at regional scales because they are biased by arbitrary null movement point references and by flattening (Tosi et al., 2013; Tosi et al., 2015).

Here, we use these interferometric products to provide a comprehensive picture of the land subsidence in the FVG coastal plain (Fig. 1) and to highlight driving mechanisms acting at the regional and local scales related to natural processes and anthropogenic activities such as groundwater exploitation, hydraulic reclamation, agriculture and urbanization.

Specifically, we apply the post-processed de-flattening procedure described by Tosi et al. (2015) necessary to obtain land displacements at millimeter-scale accuracy in large areas, as already adopted in many subsidence studies of the Venice coastlands, e.g., Teatini et al. (2012), Tosi et al. (2013), Tosi et al. (2016), and Da Lio et al. (2018). Such a procedure consists in implementing correction planes modeled through ground-based data to mitigate the slight phase tilt resulting by the imperfect knowledge of satellite positions.

This paper is organized as follows. First, the calibration and deflattening of Envisat ASAR and ERS1/2 interferometric products using ground-based measurements is discussed. Second, an analysis of the distribution and temporal evolution of land subsidence is presented. Third, potential mechanisms driving subsidence are discussed and, finally, the coastal subsidence of the FVG is compared with that of the adjacent areas of the northern Adriatic coastland.

2. Material and methods

The analysis of land subsidence in the FVG coast is based on persistent scatterer interferometry (PSI) products obtained by Envisat ASAR and ERS1/2 images and made available by the National Geoportal of the Italian Ministry of the Environment and Protection of Land and Sea (http://www.pcn.minambiente.it/mattm/en/). Specifically, we used the following datasets (Fig. 1):

- Envisat ASAR, Track 351 - Frame 2691, consisting of a stack of 37 descending stripmap images (C-band) acquired between 2003 and 2010 with a revisiting time of 35 days, quite irregular in the study area, generally spanning from 35 and 70 days;
- ERS1/2 Track 351 - Frame 2691, consisting of a stack of 72 descending stripmap images (C-band) acquired between 1992 and 2000 with a revisiting time of 35 days and quite regular acquisition in the study area.

A detailed description of the interferometric processing of these datasets has been provided by Costantini et al. (2017).

The interferometric products refer to arbitrary null displacement reference points and are affected by slight tilting due to the imperfect knowledge of satellite orbits, both issues compromising the reliability of ground movements, particularly mapping at the regional scale. To reduce these biases, calibration and de-flattening were previously performed using correction planes modeled through ground-based data (Teatini et al., 2012; Tosi et al., 2015) by i) defining a local reference frame based on a reference point located outside the study area and the subsiding coastland and ii) projecting the vertical velocities of the ground-truth data along the line of sight (LOS) of the satellites (Da Lio et al., 2018).

Four permanent continuous GPS stations (CGPS) properly distributed in the monitored area were selected from the MAGNET GPS network (IGS08 datum, e.g., Rebischung et al., 2012) and used for