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

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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/yr in the high southwestern plain toward the littoral to more than 5 mm/yr 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.

Keywords: Land subsidence, Friuli Venezia Giulia coastland, Grado-Marano lagoon, SAR interferometry

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 et al. (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/yr and a local sinking rate of 3-4 mm/yr. 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/yr 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 de-flattening 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.

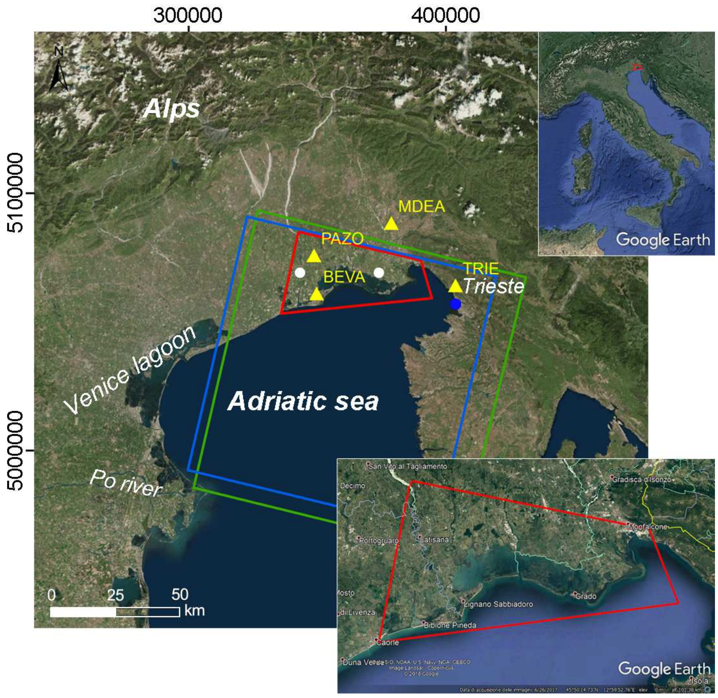

Fig. 1. Satellite image of the northern Adriatic coastland. The study area is indicated by the red polygon. The footprints of ERS1/2 (Track 351 - Frame 2691) and Envisat ASAR (Track 351 - Frame 2691) frames are represented by blue and green boxes, respectively. Yellow triangles: positions of the CGPS stations; white dots: positions of the leveling benchmarks; blue dot: tide gauge station.

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., 2011) and used for calibration and de-flattening of the Envisat interferometric product (http://geodesy.unr.edu). Specifically, three of these CGPS stations are located inside the area covered by the interferometric dataset, i.e., PAZO in the northwestern part, TRIE in the eastern part, and BEVA in the southernmost part close to the Grado-Marano lagoon and Tagliamento River; one, MDEA, lies just outside the SAR frames in the northern part of the study area and is used to refer the horizontal movements (Fig. 1). The time intervals spanned by the selected CGPS match those spanned by the Envisat ASAR data, with the exception of BEVA CGPS, which is shorter and covers only the last two years of the 2003-2010 period. For this latter dataset, we assumed negligible change in the ground movement trend.

Because ERS1/2 images were acquired prior to the installation of the CGPS stations, leveling data from the Italian Military Geographic Institute - IGMI (https://www.igmi.org/en), the former hydrographic office of the Venice Water Authority - UIMA (http://provveditoratovenezia.mit.gov.it/), and the tide gauge station of Trieste (e.g., Carbognin et al., 2010) were used to calibrate the 1993-2000 interferometric product (Fig. 1).

3. Results

3.1 Recent land subsidence over 2003-2010 period

The interferometric solutions provided by the Special Plan of Remote Sensing of the Environment refer to arbitrary null movement points and are affected by the so-called flattening problem, i.e., the slight phase tilt resulting from the inaccuracy in estimating the orbital baseline due to the imperfect knowledge of satellite positions. Therefore, we adjusted the PSI solution with a correction plane model fitting the velocities of the three CGPS (http://geodesy.unr.edu) considered as ground truths (Table 1).

The CGPS horizontal land movements refer to a fourth CGPS station (MDEA CGPS; 13° 26' 8.16" E, 45° 55' 28.20" N) located outside the study area. Because the horizontal movements (N and E) of MDEA CGPS are assumed to be representative of the regional plate motion, its average velocities in the N and E directions, i.e., 17.6 and 21.6 mm/yr, respectively, were removed from all the other CGPS stations (Table 1). In addition, considering that SAR interferometry provides land displacements along the line of sight (LOS) between a satellite and the targets, the three-dimensional CGPS velocity vectors must be projected onto the SAR LOS using Eq. (1):

$$CGPS_{LOS} = \sin(\theta)\cos(\phi)\Delta E + \sin(\theta)\sin(\phi)\Delta N + \cos(\theta)UP \qquad (1)$$

ΔE and ΔN are the local easting and northing components of the CGPS, computed by removing the E and N average velocities of MDEA, and UP is the vertical component. The incidence angle, θ, and the ground track angle, ϕ, at the CGPS locations were assumed to be equal to those of the frame, i.e., 22° and 5°, respectively (SAR metadata available from the Italian Ministry of the Environment and Protection of Land and Sea).

Table 1. Position, easting (E), northing (N), vertical (UP), and LOS velocities of the CGPS stations used for the calibration of the SAR dataset.

Station ID	Station Name	Longitude (deg)	Latitude (deg)	E (mm/yr)	N (mm/yr)	UP (mm/yr)	$CGPS_{LOS}$ (mm/yr)
PAZO	Palazzolo dello Stella (UD)	13° 03' 9.19"	45° 48' 20.60"	21.6	17.1	-1.3	-1.2
TRIE	Trieste	13° 45' 48.67"	45° 42' 35.12"	20.8	17.5	-0.5	-0.8
BEVA	Bevazzana (UD)	13° 04' 9.93"	45° 40' 18.81"	21.6	17.6	-4.4	-4.1

Finally, the differences between the $CGPS_{LOS}$ and the velocities of the PTs (Point Targets) averaged over a 200-m radius centered on the three CGPS stations were used for the tilting plane (Tosi et al., 2015) implemented to correct the interferometric products.

The velocity map of the ground movements of the FVG coast resulting from the calibration and de-flattening of the Envisat ASAR PSI products available from the Italian Ministry of the Environment and Protection of Land and Sea is shown in Fig. 2. The analysis of coastal subsidence focuses on the coastal plain with ground elevations of approximately less than 20 m above mean sea level (MSL), which includes nearly 22,000 PTs.

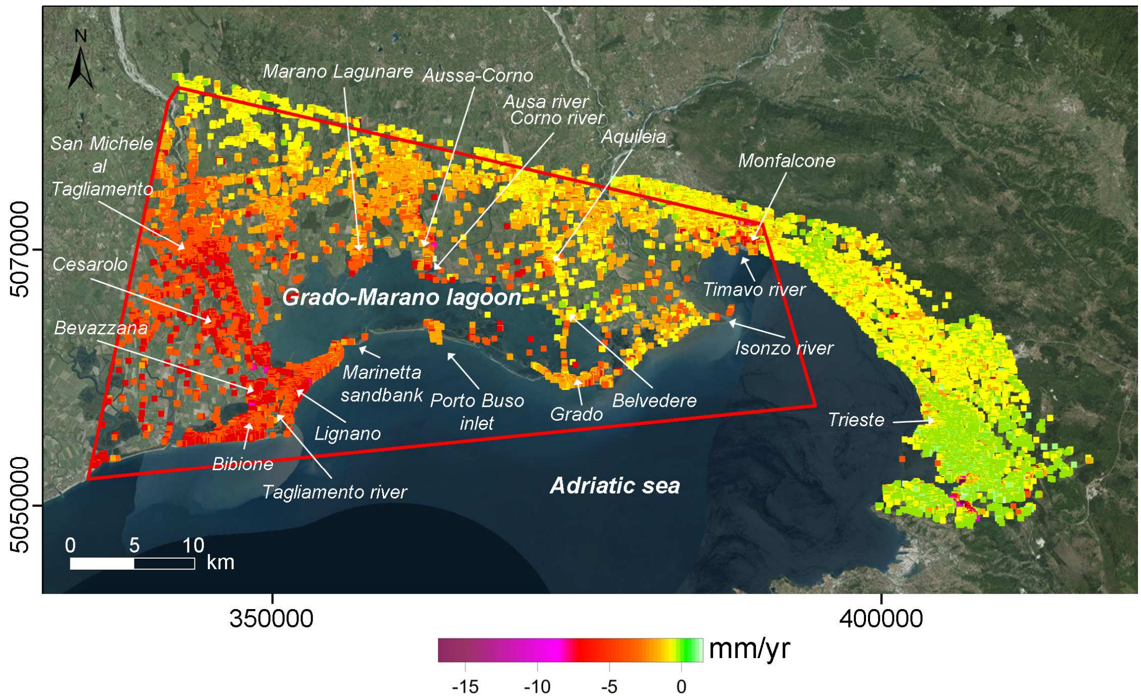

Fig. 2. Average land displacements obtained by PSI on Envisat ASAR images for the 2003-2010 period. Positive values indicate uplift, and negative values indicate land subsidence. The area delimited by the red polygon is the coastal study area with ground elevation lower than approximately 20 m above MSL.

The coastal plain is characterized by a gradient of subsidence increasing from the northern margin of the study area toward the littoral along a rather well-defined southwestern direction. Based on the relative stability of the upper portion, the average land subsidence rate increases to 2.5 mm/yr in the central part, at the boundary of the Grado-Marano lagoon, and to 4 mm/yr close to the Tagliamento River delta, where local settlements of up to 10 mm/yr have been detected.

A more detailed analysis of the land subsidence through a description of its behavior in the main sectors of the coastal plain is provided in the following.

Focusing on the littoral strip from Bibione to Monfalcone, the land subsidence trend clearly decreases eastward. However, high sinking values have been observed locally along the whole littoral. The littorals of Bibione and Lignano show quite homogeneous and significant subsidence, with average rates of approximately 4 mm/yr and local sinking of up to 10 mm/yr in the back sector of the delta at Cesarolo (Fig. 3a). Significant land subsidence rates affect the western narrow littoral separating the Grado-Marano lagoon from the Adriatic Sea, i.e., Isola Marinetta. Although statistically insignificant because only a few PTs are present, sinking values range from 2 to 4 mm/yr (Fig. 3b). More PTs are present in the jetties of the Porto Buso inlet, and although a few of them sink by as much as 4 mm/yr, rather homogenous displacement rates with an average of -2 mm/yr characterize the inlet (Fig. 3c).

The subsidence of the eastern littoral sector encompassing Grado, the Isonzo River mouth and Monfalcone is punctuated by high variability. Although the average subsidence of such areas spans from 2 and 2.5 mm/yr (significantly lower than that of the Tagliamento River delta), sinking rates as high as 10 mm/yr at Grado (Fig. 4a), 4 mm/yr in the Isonzo estuary (Fig. 4b) and 8 mm/yr in the Monfalcone industrial area (Fig. 4c) have been detected.

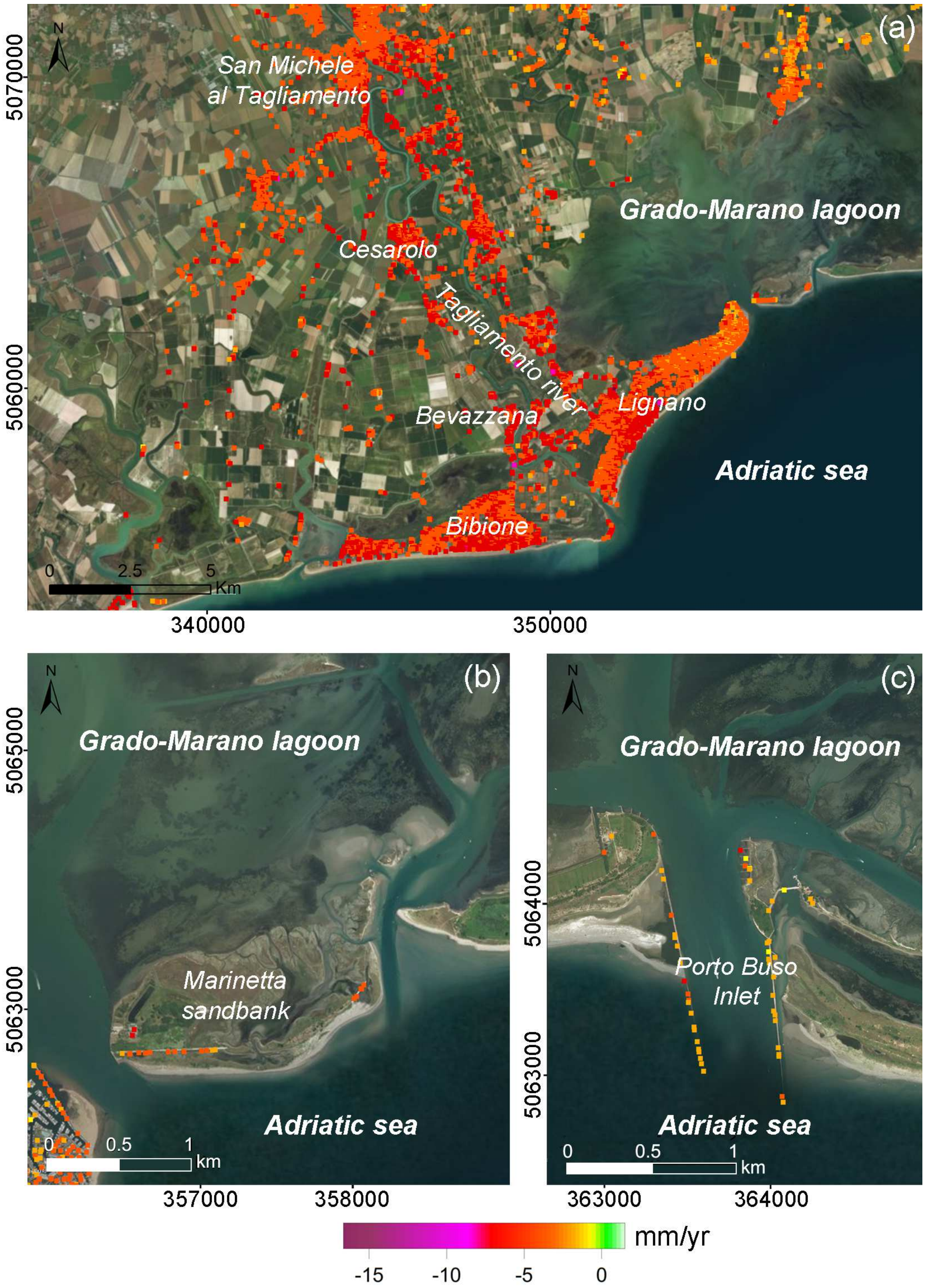

Fig. 3. Details of the average land displacements 2003-2010 at (a) Bibione and Lignano littoral and San Michele al Tagliamento in the mainland; (b) Marinetta sandbank; and (c) Porto Buso inlet. Positive values indicate uplift, and negative values indicate land subsidence.

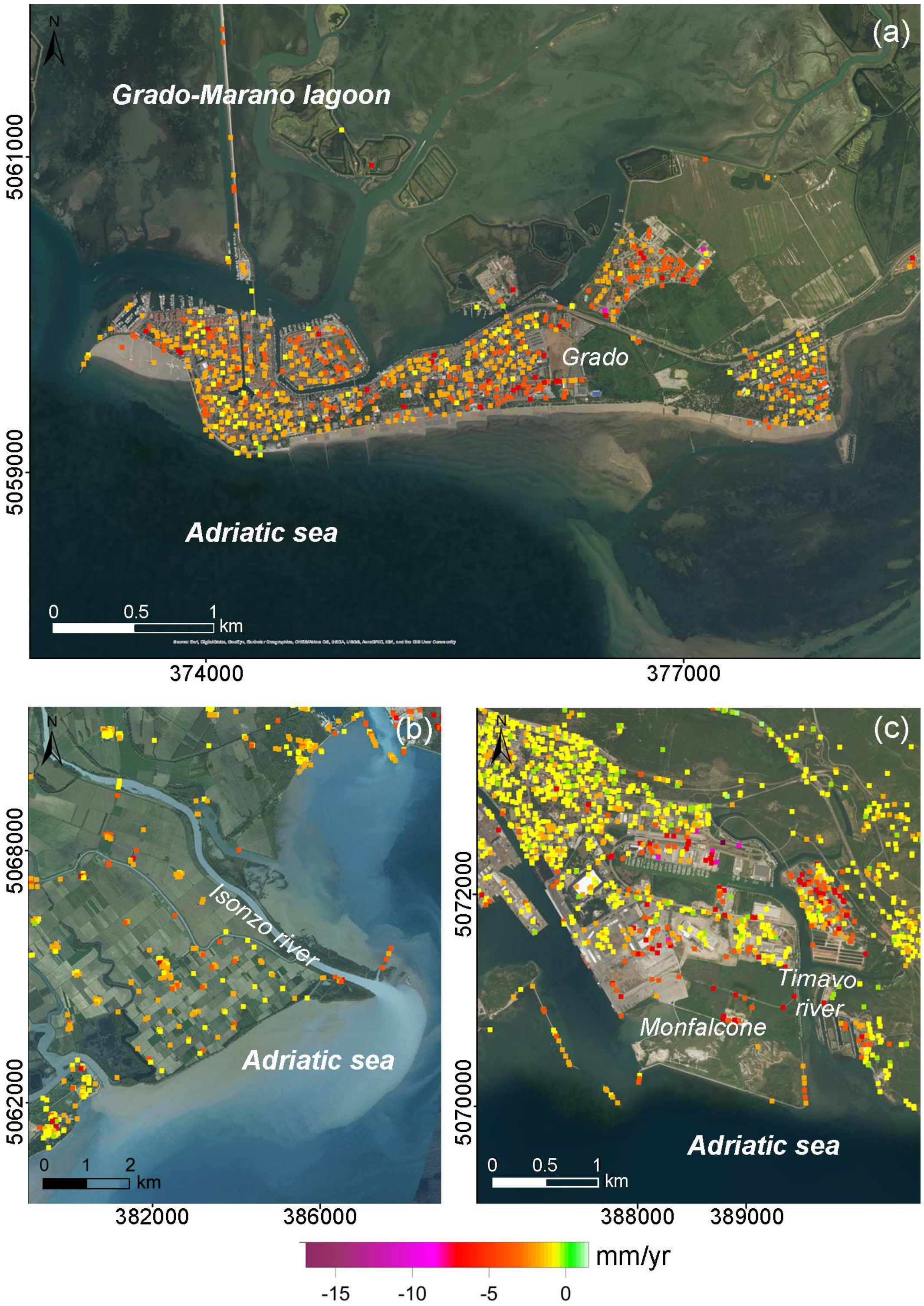

Fig. 4. Details of the average land displacements over the period 2003-2010 in the littoral strip at (a) the Grado littoral; (b) the Isonzo River mouth; and (c) the Monfalcone

industrial port area. Positive values indicate uplift, and negative values indicate land subsidence.

Moving to the lagoon of Grado-Marano, the presence of PTs is very scarce and generally limited to a few scattered salt marshes, the embankments and the bridge. The values of the displacements are quite variable, from a stable condition to approximately -5 mm/yr (Fig. 5a).

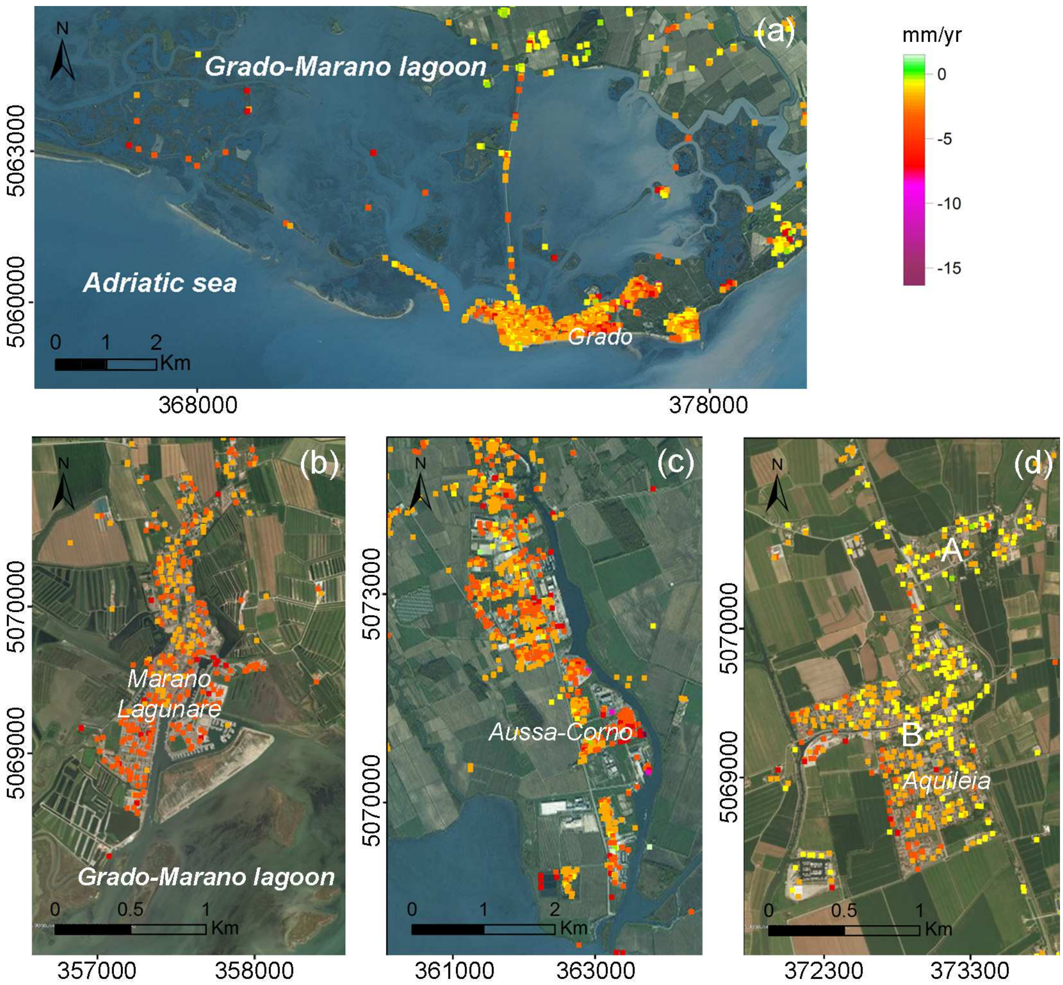

Fig. 5. Details of the average land displacements over the period 2003-2010 in the lagoon of Grado-Marano and its northern margin: (a) the lagoon; (b) Marano Lagunare; (c) the Aussa-Corno industrial area; and (d) Aquileia ancient city (A) and recent built-

up areas (B). Positive values indicate uplift, and negative values indicate land subsidence.

In the mainland bounding the northern margin of the lagoon between the Stella River mouth and the confluence of the Ausa and Corno River mouths, Marano Lagunare shows a peculiar subsidence pattern with the sinking rate increasing to 7 mm/yr toward the lagoon (Fig. 5b). In the eastern part of Marano Lagunare, uneven subsidence was detected in the industrial zone of Aussa-Corno (Fig. 5c). Although the average subsidence is approximately 2.5 mm/yr, the ground movements range from negligible values to more than -10 mm/yr.

Uneven sinking rates were also detected at Aquileia, which includes archeological and newly built-up areas. The newly developed residential district shows a sinking rate of approximately 4 m/yr, with some spots exhibiting rates as high as 5 mm/yr, while in the ancient city, established in Roman times, the land subsidence rate is generally lower than 2 mm/yr (Fig. 5d).

Moving to the mainland, the area most strongly affected by land subsidence is located between San Michele al Tagliamento and Bevazzana, where it averages approximately 3.5 mm/yr, with homogeneous local sinking sectors exhibiting rates as high as 5 mm/yr (Fig. 3a).

3.2 Historical land subsidence over 1992-2000 period

The availability of the SAR interferometric products retrieved by ERS1/2 images allows for the analysis of land subsidence to extend back to the 1992-2000 period (Fig. 6).

The ERS interferometric dataset was corrected and calibrated using a tilting plane model computed by the differences between SAR and ground-based velocities in three sites: Trieste, San Michele al Tagliamento and Belvedere. According to a number of studies based on long-term relative sea level data recorded at the tide gauge of Trieste (e.g., Carbognin et al., 2010; Carbognin et al., 2011), null ground movements were assumed at the tide gauge of Trieste for SAR data displacements. An average displacement of -4 mm/yr was assumed for the San Michele al Tagliamento site, as detected by the 1989-2002 leveling (e.g., Antonioli et al., 2009), and an average displacement of -1.2 mm/yr was assumed for the Belvedere site, whose subsidence rates remain nearly unchanged over the 1980-2004 period, as demonstrated by the 1980-1997 and 1997-2004 levelling data (Marchesini, 2006). Because CGPS stations were absent during the ERS1/2 acquisition time span, correction due to differential horizontal displacements is not possible. However, considering that the study area is quite uniformly moving northeastward (Table 1) with respect to the plate motion and there is low sensitivity to the horizontal components of the displacement because the average incident angle of ERS1/2 acquisitions is approximately 23°, we can reasonably assume that the horizontal component of the LOS is negligible with respect to the vertical one.

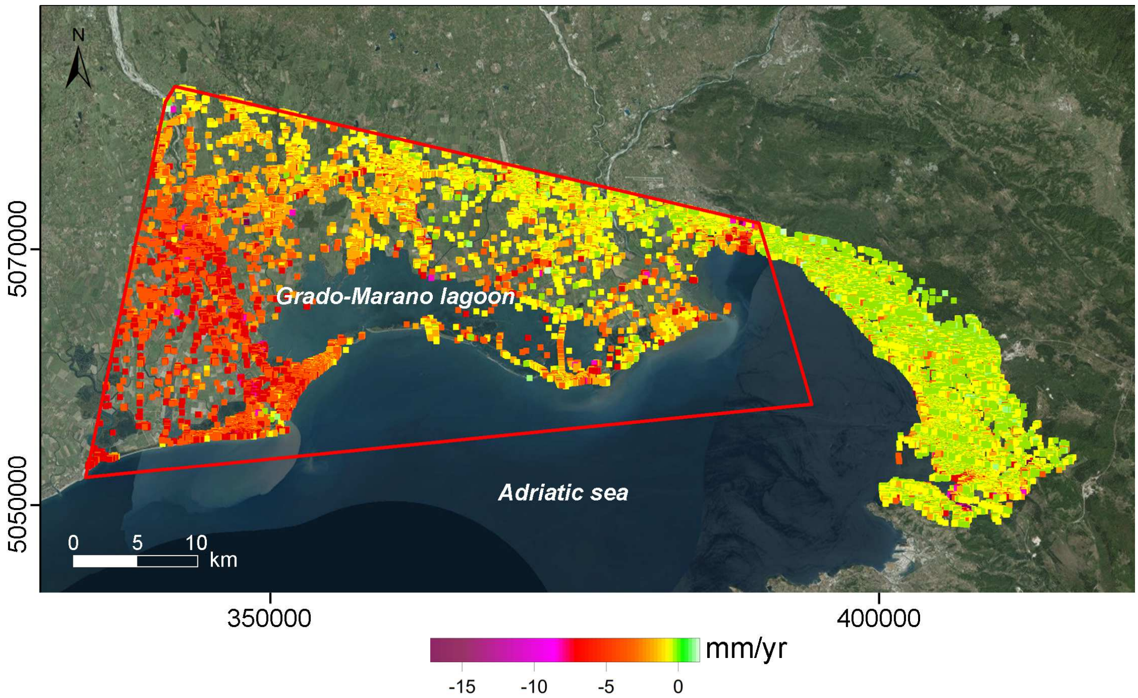

Fig. 6. Average land displacements obtained by PSI on ERS1/2 images for the 1992-2000 period. Positive values indicate uplift, and negative values indicate land subsidence. Red polygon bounds the coastal study area with ground elevation lower than approximately 20 m above MSL.

The image of the 1992-2000 ground displacements at the regional scale is quite similar to that obtained for the 2003-2010 period, i.e., an increasing subsidence trend toward the southwestern part of the FVG coastland. A more detailed analysis was performed comparing the ground velocities measured over the periods 1993-2000 and 2003-2010 in three areas characterized by different land subsidence patterns, i.e., sectors A, B and C in Fig. 7. In the 2003-2010 period, the average land subsidence rates are 3.7 ± 0.9 mm/yr, 2.1 ± 0.9 mm/yr and 1.5 ± 0.8 mm/yr for areas A, B and C, respectively, while in the previous time span the average land subsidence rates are 3.5 ± 1.2 mm/yr, 1.8 ±

1.1 mm/yr, and 1.1 ± 1.0 mm/yr, respectively. The frequency distributions of these average displacement rates are shown in Fig. 7.

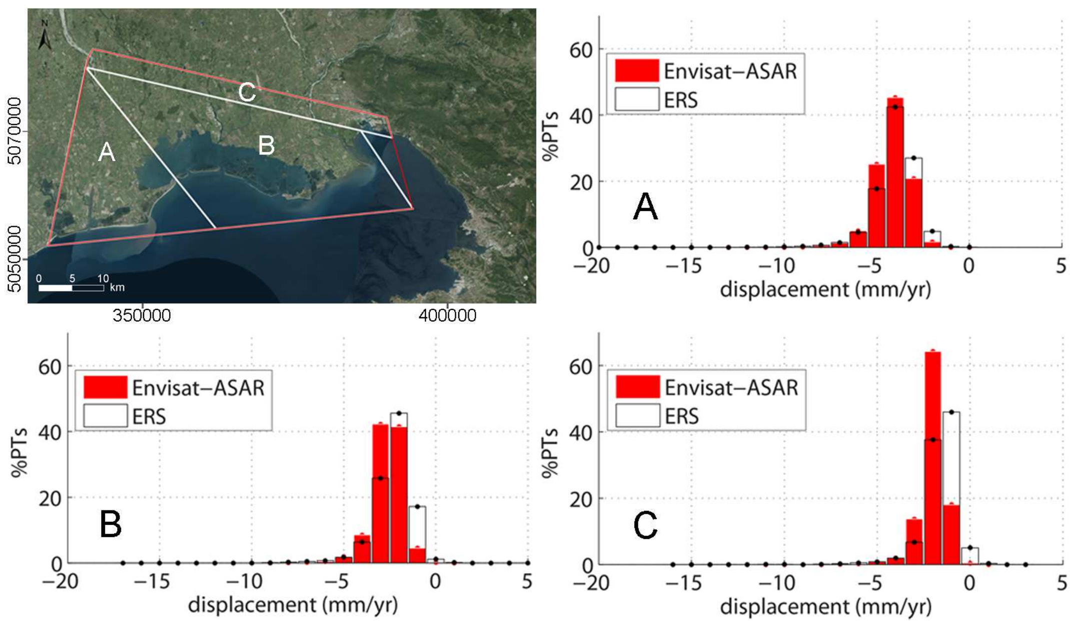

Fig. 7. Frequency distribution of the 1993-2000 (white) and 2003-2010 (red) average ground movement rates in sectors A, B, and C of the FVG coastal plain shown in the satellite image.

To quantify the land movement differences at the regional scale between the 2003-2010 and 1992-2000 time spans, two calibrated and de-flattened interferometric solutions were interpolated using the Kriging method on the same regular 500-m grid, i.e., a compromise based on the distribution of the displacement data, covering the considered coastal plain. Then, the land subsidence change (δ) was computed for each node (Eq. 2):

$$\delta = \lambda_{2003-2010} - \lambda_{1992-2000} \quad (2)$$

where $\lambda_{2003-2010}$ and $\lambda_{1992-2000}$ are the interpolated land velocity values.

It should be noted that for a more correct quantification of the two subsidence datasets, the relatively large area of Grado-Marano lagoon not covered by PTs was removed for this type of analysis.

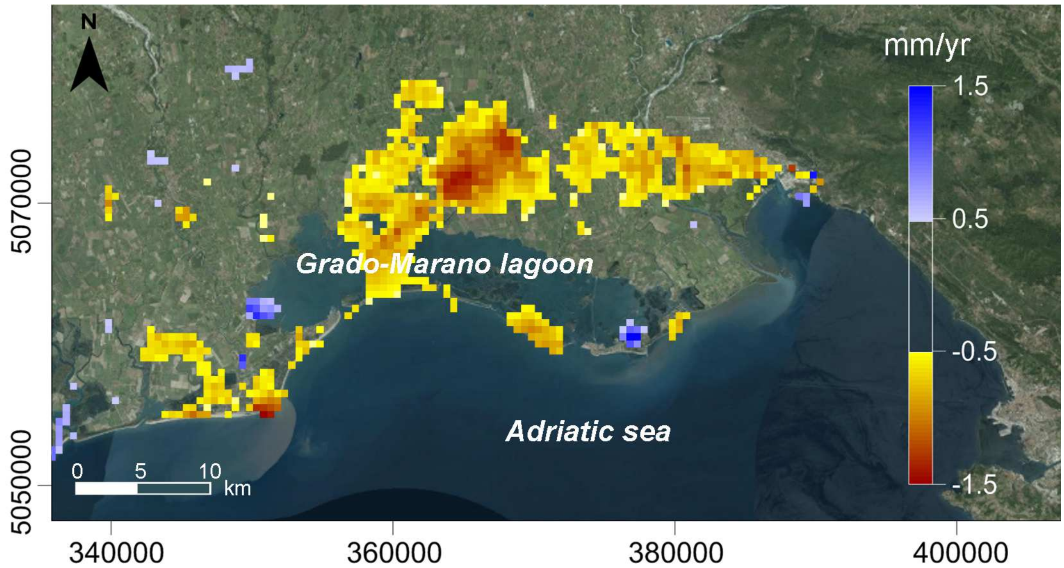

Fig. 8. Land subsidence change (δ) obtained by the difference between the 2003-2010 and 1992-2000 velocities interpolated on a regular 500-m grid.

The results show δ values ranging from 0.8 to -1.3 mm/yr (Fig. 8). These findings indicate that, despite slight increases in land subsidence in the central part of the study area, any other consideration of the velocity changes is almost speculative, as the values are within the range of uncertainty, i.e., the incorporation of the SAR method affects the assumptions made in the calibration procedures and the interpolation models.

3.3 Long-term land subsidence over the 1992-2010 period

The average land velocity map for the period 1992-2010 (Fig. 9) was obtained as follows. First, cumulative land subsidence from 1992 to 2010 ($\Lambda_{1992-2010}$) was computed for each grid node as follows (Eq. 3):

$$\Lambda_{1992-2010} = 11 \cdot \lambda_{1992-2000} + 8 \cdot \lambda_{2003-2010} \qquad (3)$$

where 11 and 8 are the time spans considered to compute the displacements. It should be noted that the cumulative land subsidence from 1992 to 2000 obtained by ERS1/2 was multiplied by 11 years, assuming the same average velocities for the period 2001-2002. The long-term land subsidence between 1992 and 2010 ($\overline{\Lambda}_{1992-2010}$) was then derived as the mean value over the total time frame of 19 years; the modeling outcome is shown in Fig. 9.

The $\overline{\Lambda}_{1992-2010}$ map confirms the general increasing trend toward the southwestern part of the study area close to the Tagliamento River and the significant heterogeneity of the subsidence in the coastal plain at the regional scale, with velocities spanning from less than 1 mm/yr to more than 5 mm/yr. Notably, the interpolated map provides a reliable image of the land subsidence at the regional scale as it significantly smooths local high sinking also present where average values are not particularly high.

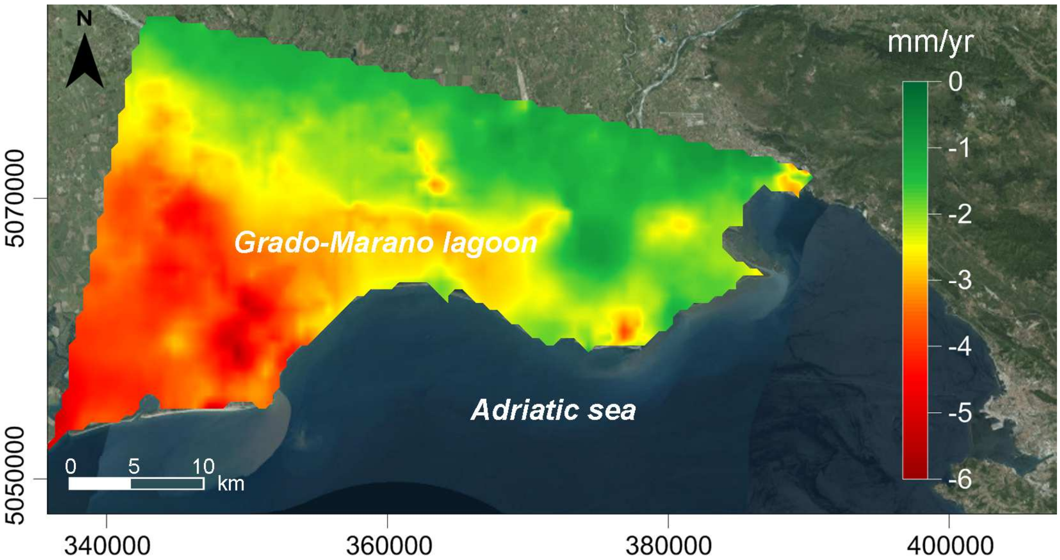

Fig. 9. Long-term land subsidence $\overline{\Lambda}_{1992-2010}$ computed on a regular 500-m grid for the 1992-2010 period. Positive values indicate uplift, and negative values indicate land subsidence.

4. Discussion

4.1 Regional subsidence

This study depicts an image of the land subsidence of the FVG coastal plain delineating a regional gradient that increases seaward, with maximum sinking rates in the area adjacent to the Tagliamento River delta and various local heterogeneities superposed.

Land subsidence is the result of natural processes and anthropogenic activities, hardly quantifiable separately but whose prevailing contributions are likely identifiable. Tectonics (including Glacial Isostatic Adjustment-GIA and bedrock accommodation) and compaction of the subsoil are among the main natural components of regional land subsidence.

In the FVG region, the high-subsidence sectors (Fig. 2, Fig. 6, Fig. 9) are well correlated with the deeper base of the Pre-Quaternary deposits (Fig. 10a). Moreover, considering the FVG plain divided by the Dinaric thrust in two main sectors corresponding to the different bedrock types, i.e., the Pliocene and Flysh formation (Fig. 10a) (Busetti et al., 2009), the higher sinking zone is located in the former.

Regarding the component of the land subsidence due to the shallow subsoil geomechanical characteristics, recent studies have noted that in many coastal plains the compaction of the younger Holocene subsoil is significantly higher than that of the Pleistocene sediments (Törnqvist et al., 2008; Higgins et al., 2014). This correlation has also been observed for the Holocene marine-lagoon and the alluvial last glacial maximum (LGM) and pre-LGM deeper deposits by Tosi et al. (2009) and Teatini et al. (2011) in the Venice and Po delta regions, respectively. However, the high-sinking sectors and the major thickness of the Holocene deposits are not correlated everywhere in the FVG coastal plain (Fig. 10a,b) as in the higher course of the Tagliamento River (San Michele al Tagliamento area), where the major contribution to the subsidence is due to groundwater exploitation.

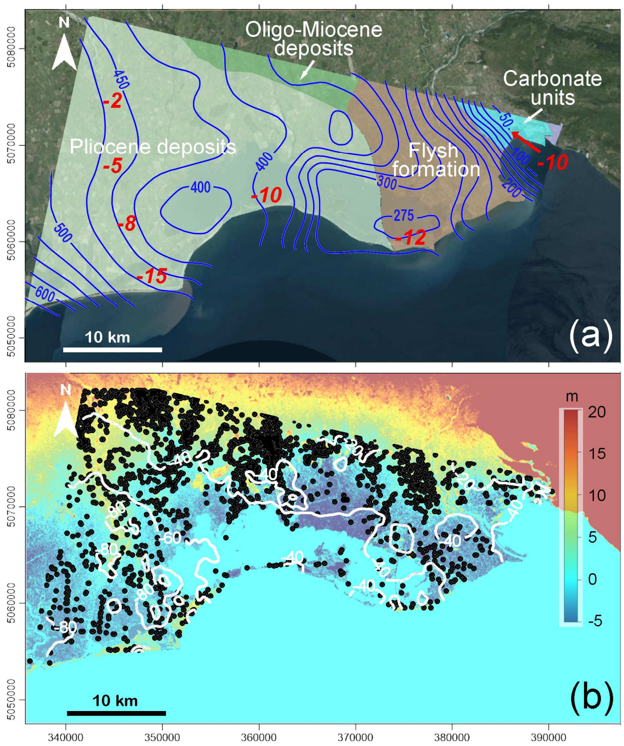

Fig. 10. Geologic and morphologic setting of the study area. (a) Map of the depth (m) of the Quaternary base (blue contour lines) (from Regione Friuli Venezia Giulia, 2014) superimposed on the units of Pre-Quaternary deposits (from Busetti et al., 2009). Red numbers refer to the approximate thickness (m) of Holocene deposits (from Amorosi et al., 2008; Bondesan et al., 2008; Marocco and Melis, 2009; Trobec et al., 2017). (b) Map of cumulative land subsidence $\Lambda_{1992-2010}$ (mm) (white contour lines) over the 1992-2010 period superimposed on the elevation map of the coastland (SRTM 1 Arc-Second data from USGS Earth Resources Observation and Science (EROS) Center). Black dots refer to the groundwater well positions (from Regione Friuli Venezia Giulia, 2014).

Regarding the induced subsidence, groundwater withdrawals, hydraulic reclamations and urbanization are the most common causes of land subsidence. In the FVG coastal plain, groundwater is exploited for various purposes (e.g., drinking, agricultural, industrial, fish breeding) from a multilayer aquifer system consisting of six main aquifers down to a depth of approximately 500 m (Rapti-Caputo et al., 2009; Zini et al., 2013). In the deeper aquifers, particularly those close to Tagliamento River delta, thermal waters are also exploited (Stefanini et al., 1976; Stefanini et al., 1977; Stefanini et al., 1978). The western areas are the most significantly subsiding sectors (Fig. 2). In particular, the areas adjacent to the Tagliamento River course, such as San Michele al Tagliamento, Cesarolo and Bevazzana, show sinking rates as high as 5 mm/yr and locally greater values. Groundwater is exploited in the NW sector as well, but the presence of a low-compressibility gravel-sand rich subsoil likely renders land subsidence negligible (averages to 0.7 mm/yr) (Fig. 2). Similar subsidence rates characterize the Venice high plain, close to the alpine foothills, which shows analogous characteristics with respect to the subsoil setting and groundwater use (Tosi et al., 2016).

A study including, for instance, measurements of groundwater levels, groundwater pumping and aquifer recharge should be conducted to quantify the role of groundwater exploitation in driving land subsidence, based on the groundwater use provided by Treu (2011). However, we highlight that in higher sinking areas such as the Tagliamento River course, the littoral of Grado and the northern lagoon margin, a significant number of wells are present. Nevertheless, it should be noted that a high density of wells is also located in the northern plain, where land subsidence is negligible. This issue also concerns the Venice area (Da Lio et al., 2013; Da Lio et al., 2015) and the Po River delta, where updating of the groundwater monitoring network and quantification of pumping are necessary to understand unclear local and regional subsidence patterns (Tosi et al., 2016).

High subsidence rates are also typically common in low-lying coastlands corresponding to ancient marshes and lagoons, today hydraulically drained and transformed into farmlands. Land subsidence in such environments generally combines the compaction of the relatively recent soft deposits with the loss in ground elevation due to oxidation of peaty soils driven by hydraulic reclamation and agricultural activities (Gambolati et al., 2005; Deverel et al., 2016; Zhou et al., 2016). In the FVG coastal plain, a clear correlation between the low-lying reclaimed areas and the higher land subsidence sectors is found only in the western lowlands corresponding to the lower Tagliamento River course but not in the central and eastern sectors, where subsidence is not significant (Fig. 10). One possible explanation of this low sinking is the presence of exposed LGM and pre-LGM deposits (Fontana et al., 2008; Fontana et al., 2010; Zanferrari et al., 2014) rather than the younger Holocene back-barrier deposits. Moreover, the analysis of these low-lying sectors may have been biased because of the presence of PTs mainly in stable structures, i.e., located on sandy layers (e.g., paleo-channels) not involved in the organic soil oxidation or founded in deep subsoil, rather than in the farmlands where the C-band sensors are typically unusable for measuring land movements because of the presence of vegetation. This issue has already been noted by Teatini et al. (2005) and Teatini et al. (2007) in similar vegetated areas of the Veneto coastal plain and partly overcome by combining L-band and X-band sensors (Tosi et al., 2016) and using artificial corner reflectors (Strozzi et al., 2013).

4.2 Comparison with adjacent similar hydro-geomorphologic settings

Land subsidence of the FVG coastal plain has been compared with that of the adjacent Venice - Po River delta region under similar hydro-geomorphologic settings of the littoral and mainland sectors.

4.2.1 Littoral sector

The Tagliamento delta (Fig. 3a) is characterized by an average subsidence rate of approximately 4 mm/yr, which is significantly lower than the rates of up to 10-15 mm/yr measured in the Po River delta lobe by Teatini et al. (2011) and Tosi et al. (2016). The higher thickness of the Holocene highly compressible prodelta muds and the very fast delta progradation occurring over the past 500 years (Sestini, 1996; Teatini et al., 2011; Tosi et al., 2016) make the Po River deltaic area more prone to sinking than the Tagliamento River deltaic area, although groundwater exploitation should contribute to the sinking area around Bibione and Lignano (Tosi et al., 2007). In contrast, land subsidence at the Piave and Tagliamento River mouths (Tosi et al., 2016) is more comparable because of the similar subsoil and land use characteristics of the regions.

Moving to the eastern littoral strip bounding the Grado-Marano lagoon (Fig. 3b,c), the average land subsidence of the Marinetta sandbank is approximately 2.5 mm/yr. Most of the PTs refer to the stone embankments built for protecting the littoral from erosion and storm waves. This value is quite similar to that measured in the older stone embankments bounding the fish farms at the Cavallino – Treporti littoral (Venice), where sandy layers prevail in the shallow subsoil (Tosi et al., 2010). The jetties built in the early 1960s at Porto Buso inlet show slow sinking rates of approximately 2 mm/yr, similar to those occurring in the older and well-consolidated parts of the jetties of the Venice lagoon inlets, which were not addressed by recent MoSE studies (Strozzi et al., 2009; Tosi et al., 2012).

The littoral of Grado (Fig. 4a), a sector mostly devoted to tourism, shows uneven subsidence due to the combination of subsoil heterogeneity, groundwater exploitation and loads induced by newly built-up sectors, quite similar to the characteristics detected at Jesolo (northern Venice littoral), where analogous subsidence driving mechanisms are present (Tosi et al., 2015).

The variability of the land subsidence measured at the Isonzo River mouth, ranging from 0.5 to 5 mm/yr (Fig. 4b), reflects the heterogeneity of the shallow subsoil related to i) the coastal evolution of the littoral - back barrier system over the early Holocene and ii) the later eastward shifting of the river mouth to the current position. These features have provided opportunities to reclaim wetlands, often rich in organic deposits, today (Marocco, 1989).

High variability of land subsidence (from less than 1 to 6-8 mm/yr) also characterizes the easternmost part of the coastal sector corresponding to the Monfalcone industrial and harbor area (Fig. 4c). Groundwater extraction for industrial and geothermal use (Treu, 2011) along with the load of infrastructures and facilities are likely the causes of the major distribution of land sinking, while the subsoil architecture plays an important role in shaping subsidence heterogeneity. The marshy area located at the foot of the Karst near the mouth of the Timavo River (Monfalcone) corresponds to a Roman time large lagoon (e.g., Insulae Clarae, Lacus Timavi) progressively filled by sandy-pelite marine and alluvial deposits (e.g., Marocco and Melis, 2009) to form a salt marsh environment, recently reclaimed to develop the industrial area. The carbonate bedrock lies at depths of 30-40 m and 10-20 m in the eastern and western sector, respectively (e.g., Marocco and Melis, 2009). As the land subsidence rates for the active residual consolidation increase, the infilling thickness of the ancient lagoon basin increases.

4.2.2 Lagoon sector

Most of the PTs refer to land subsidence because even a small loss in ground elevation combined with the increasing sea level rise may threaten its survival. The intrinsic capacity of salt marshes to keep pace with the relative sea level rise (Rizzetto and Tosi 2011; Rizzetto and Tosi 2012) largely depends on soil compaction and sediment availability (Zoccarato et al., 2017) as well as bio-morphological processes (Marani et al., 2013). The subsidence of the Grado-Marano lagoon averages approximately 2 mm/yr (Fig. 5), although salt marshes and lagoon embankments sink more rapidly because of multiple causes, which include natural consolidation of different thicknesses of Holocene subsoil, groundwater exploitation and likely the instability of embankments bounding the northern lagoon margin (Fontolan et al., 2012). Similar behavior characterizes the lagoons of Venice and the Po River delta (Tosi et al., 2010; Tosi et al., 2016; Da Lio et al., 2018). The scarcity of PTs in the Grado-Marano lagoon related to the temporal decorrelation of the radar signal due to the presence of vegetation do not allow for a detailed analysis or quantification. Further application of ad hoc SAR strategies, i.e., the use of artificial corner reflectors and the combination of the X and L bands, as various authors have recently tested (Nitti et al., 2009; Strozzi et al., 2013; Luo et al., 2014; Tosi et al., 2016; Da Lio et al., 2018), could be crucial to overcome this limitation.

4.2.3 Mainland sector

The subsidence of the mainland bounding the northern lagoon margin ranges from a stable condition to 8 mm/yr (Fig. 2). In the western margin (e.g., Bevazzana, Cesarolo, San Michele al Tagliamento in Fig. 3a), groundwater is widespread, and spatially marked variations in subsidence do not occur, while in the central and eastern margins, the new built-up areas (e.g., Marano Lagunare, Aussa-Corno, Aquileia in Fig. 5b,c,d) show extensive sinking. The transition from marine-lagoon Holocene deposits to the alluvial units is strongly correlated with the heterogeneity of ground movements. The archaeological area of Aquileia, which is on the UNESCO World Heritage Sites List for Early Roman Empire and Middle Age remnants, requires particular attention. Ground movements are quite negligible, whereas sinking sectors reaching subsidence rates as high as 5 mm/yr are detected in the newly urbanized areas (Fig. 5d). This finding reflects the diverse consolidation history and the dominantly clayey subsoil in the newly built-up area (Alfarè et al., 2014). Similar subsidence behavior has been detected in the archaeological area of Altino (Carbognin et al., 1995; Tosi et al., 2016), located in the NW Venice lagoon margin and in the historical center of Venice and Chioggia (Tosi et al., 2016), where the consolidation rate of ancient well consolidated deposits is 0.5-1 mm/yr and only the newly built-up sites locally show high sinking rates. A different situation characterizes the coastal area of Ravenna (Emilia-Romagna region), where groundwater exploitation has induced severe land subsidence: More than 1 m accumulated during the 1950-1980 period at Porta Adriana in the historical center of Ravenna, and rates as high as 40 mm/yr were measured in 1972-1977 in the area of Lido di Classe (Teatini et al., 2005 and reference therein), where the former port established in the Roman period was located (Mauskopf Deliyannis, 2010).

As urbanization is often a cause of land subsidence in coastal plains, as the new loads associated with buildings on relatively recent deposits induce their consolidation even over periods longer than one decade (Yan et al., 2002; Bianchini et al., 2015; Chen et al., 2015; Erkens et al., 2015), we report three cases of sinking sectors due to newly built-up areas, i.e., the eastern part of the Grado littoral facing the lagoon, the Aussa-

Corno industrial area and Aquileia along the northern lagoon margin (Fig. 11). The correlation between the high subsidence rates and the age of the construction of the buildings is clearly demonstrated by the average land displacements maps. Over the 1992-2000 period, the newly built-up areas established during the end of the 1980s and the beginning of 1990s experienced higher subsidence rates than did the nearby sectors where urbanization is older (Fig. 11). Reduced sinking appears to characterize the later period. Similar behavior has been observed in the Venice area by Tosi et al. (2015) at Chioggia and Jesolo, where local bowls showing subsidence rates of up to 10 mm/yr—associated with the construction of new large buildings—have been detected.

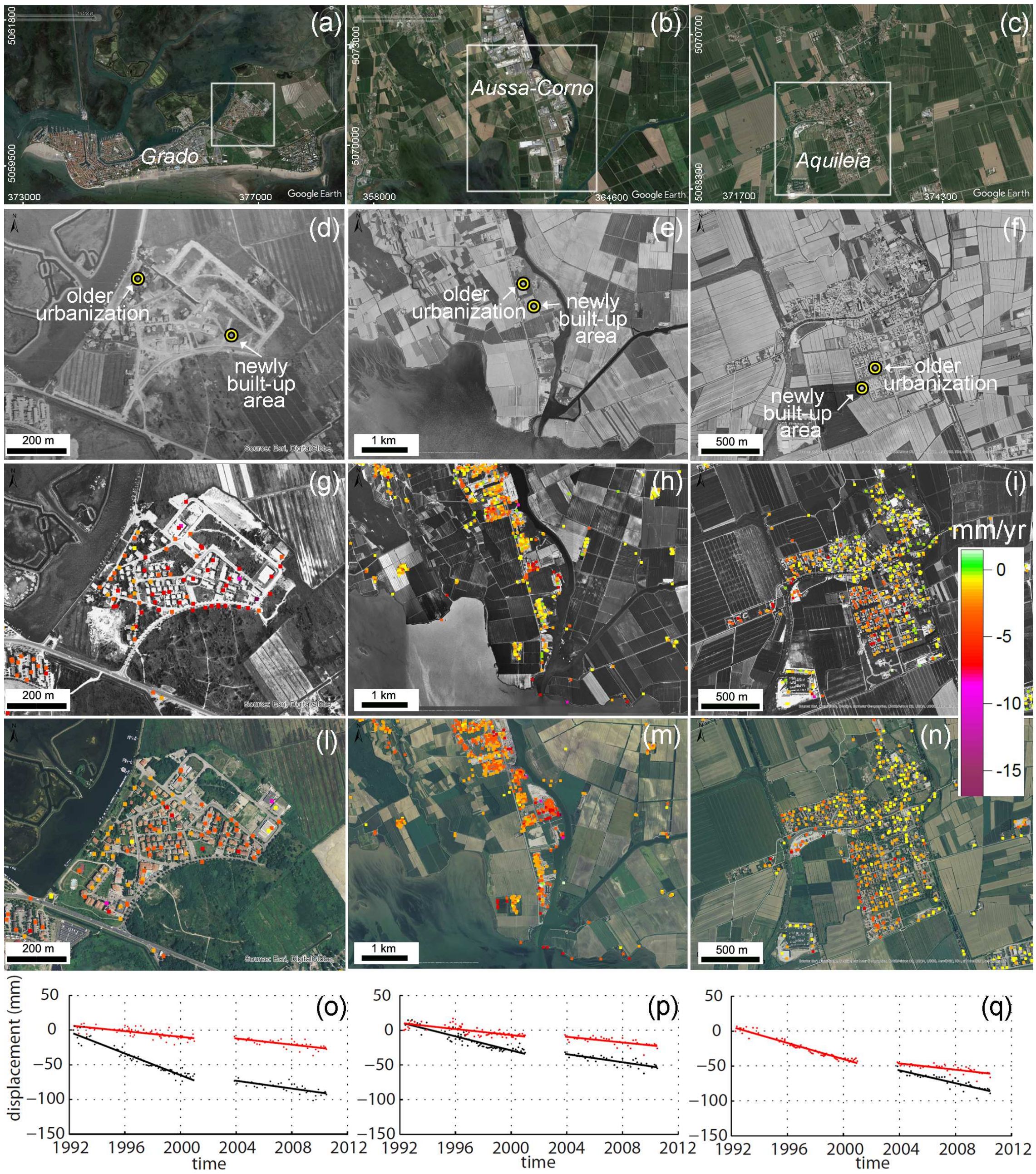

Fig. 11. Land displacements in older and newly built-up areas at (a) the Grado littoral; (b) Aussa-Corno; and (c) Aquileia. The 1989 (d-f), 1994 (g-i) and 2006 (l-n) aerial photograph bases are used as references for older urbanization and the 1992-2000 and 2003-2010 ground displacement velocities, respectively. Positive values indicate uplift, and negative values indicate land subsidence. Examples of land displacement time

series (1992-2010) in older urbanization (red) and newly built-up areas (black) at (o) the Grado littoral; (p) Aussa-Corno; and (q) Aquileia.

5. Conclusions

The FVG coastal plain, similarly to most low-lying coastal plains worldwide, is highly sensitive to the loss in elevation due to sea level rise and land subsidence. While the subsidence of the main Adriatic coastal plains has been monitored for more than a century, in the FVG coastland, the process is still poorly understood. This study characterized land subsidence of this coastal region, improving knowledge of the ground vertical displacement dynamics.

Detailed land subsidence maps of the entire FVG coastal plain, with high spatial resolution and good accuracy, have been obtained by SAR-based interferometric datasets covering the 1992-2010 period as a result of their calibrations and corrections. Although this study does not aim to rigorously quantify the various components acting on the process, likely potential land subsidence driving mechanisms have been proposed and discussed, considering the various morpho-hydro-geological settings of the FVG coastal plain.

The main outcomes are summarized as follows:

- Calibrated SAR-based interferometry provided an original and comprehensive mapping of land subsidence in the FVG coastland during the study period, allowing for both “regional-” and “local-” (few km^2) scale high-resolution data in areas never investigated previously because of the lack of leveling lines.
- On average, land subsidence rates range from less than 1 mm/yr to 5 mm/yr, with some PTs exhibiting rates greater than 10 mm/yr.

- The cumulative land subsidence over the period 1992-2010 reaches 100 mm.
- The comparison between land subsidence occurring during the period 2003-2010 and that occurring during the period 1992-2000 reveals no significant changes.
- A regional subsidence gradient increasing SW from the inland toward the coast is correlated with the different geological settings forming the various sectors of the coastal plain.
- The regional land subsidence mainly depends on geologic characteristics, such as the bedrock setting and the thickness of the Holocene deposits.
- Land subsidence heterogeneities occurring at the local scale are likely related to land use, including groundwater exploitation, and these local effects are superposed onto the regional trend mainly driven by the subsoil setting.
- The newly built-up areas show higher subsidence rates than other areas, which generally decrease over time. Nevertheless, after two decades, these areas are subsiding more strongly than are the nearby sectors, where urbanization is more established.

This study clearly highlights the need to update the analysis of land subsidence in the FVG coastland for improving data coverage as well as distinguishing and quantifying natural and anthropogenic driving processes. This issue should be addressed by the new generation of satellite SAR platforms combined with an analysis of interferometric products from different bandwidth sensors. In addition, the installation of a proper network of artificial corner reflectors will allow for the detection of ground movements in the inner lagoon, where radar reflecting structures are lacking.

In conclusion, the new knowledge on land subsidence in the FVG region encourages further monitoring investigations aimed at improving the numerical simulation of land subsidence and alternative management scenarios for sustainable groundwater exploitation. Specifically, these investigations should include monitoring of groundwater levels, quantification of groundwater pumping and aquifer recharge together with an accurate analysis of the land use changes occurring over the past decades. Although subsidence is not particularly severe in the FVG coastland, further loss of elevation with respect to the mean sea level will likely exacerbate the effect of other processes such as coastline erosion, coastal inundation and saltwater intrusion, with serious social and environmental impacts that are also related to expected global climate change.

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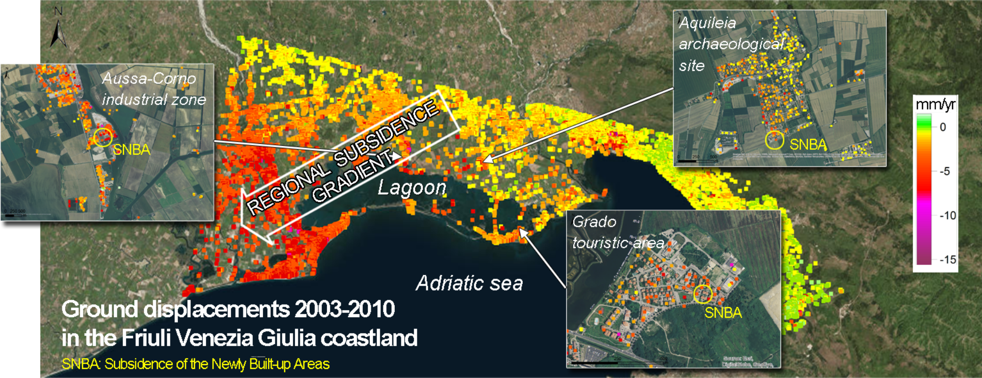
N
Aussa-Corno
industrial zone
SNBA
REGIONAL SUBSIDENCE
GRADIENT
Lagoon
Adriatic sea
Aquileia
archaeological
site
SNBA
Grado
touristic area
SNBA
mm/yr
0
-5
-10
-15
Ground displacements 2003-2010
in the Friuli Venezia Giulia coastland
SNBA: Subsidence of the Newly Built-up Areas