SUBSIDENCE DUE TO PEAT SOIL LOSS IN THE ZENNARE BASIN (ITALY): DESIGN AND SET-UP OF THE FIELD EXPERIMENT

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Abstract.

The Zennare Basin has been selected to represent the peat soil agricultural farmland of the south catchment of the Lagoon of Venice. The area was reclaimed during the 1930's and at present lies almost entirely below mean sea level (down to – 4 m a.s.l.). The extensive land subsidence that occurred since reclamation is primarily caused by the loss of sediment mass due to oxidation of the organic soil component, with consequential CO_2 gas release into the atmosphere. Because the process is essentially controlled by soil temperature and moisture, a field experiment has been designed and implemented for the determination of the relationships that control the CO_2 fluxes from the soil and the land sinking rates.

1. *Introduction.*

In the U.S. system of soil taxonomy, organic soils (or histosols) are formally defined as soils having more than 50% organic matter in the upper 80 cm [Soil Survey Staff, 1975] and commonly termed "peats". According to this definition, peat soils in Italy cover about 1200 km^2 [Andriesse, 1988]. A significant fraction of this extent is located in the low-lying

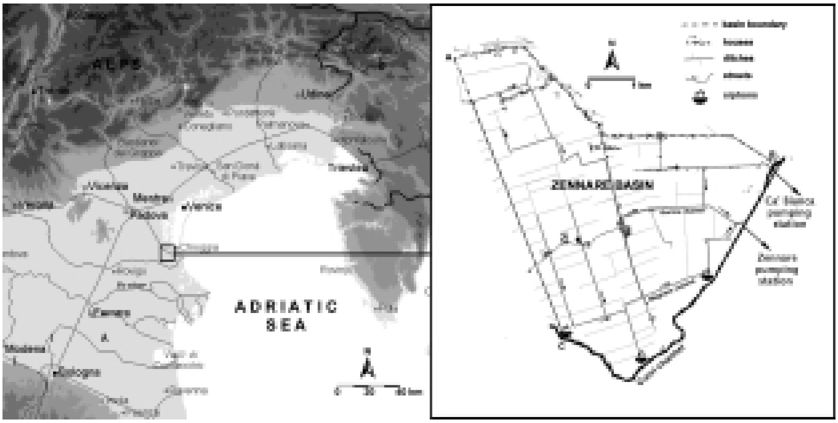

Fig. 1 – (a) Map of the Eastern Po plain with the location of Zennare Basin. (b) Schematic representation of the Zennare Basin with the location of the principal drainage network and hydraulic structures.

coastal areas of the Eastern Po river plain (Fig. 1a) and are originated from wetland reclamation during the last few centuries.

Land subsidence is the most commonly observed response of histosols to drainage for agricultural purposes. Worldwide subsidence rates in drained peaty areas vary from less than 1 cm/year to more than 10 cm/year. The oldest records of land subsidence are from the polders of the Western Netherlands, reclaimed in a period between the 9^{th} and the 13^{th} centuries, which subsided by only 1.5-2 m in about 800 - 1000 years (approximately 1.7 mm/year) [Nieuwenhuis and Schokking, 1997]. In the Everglades of Florida the arable organic soils experienced an average subsidence rate of 2.5 cm/year between 1924 and 1978 [Ingebritsen et al., 1999] and the histosols of the Sacramento-San Joaquin delta in California settled at a rate of up to 8 cm/year between 1922 and 1950 [Rojstaczer and Deverel, 1995]. Records of land subsidence in Malaysia reveal that the subsidence rates decreased from 12 cm/year over the period 1960 - 1974 to 6.4 cm/year in the following 14 years and to 2 cm/year thereafter [Wösten et al., 1997].

Under drainage, at least five sources of organic soil subsidence have been recognized [Stephens et al., 1984]: shrinkage due to desiccation, consolidation, wind and water erosion, burning, and biochemical oxidation. The latter has been found to be the dominant cause of land subsidence in temperate and tropical peat soils [Andriesse, 1988; Deverel and Rojstaczer, 1996]. Under natural waterlogged conditions, the soil is anaerobic (oxygen-poor) and organic carbon accumulates faster than it can decompose. Drainage for agricultural purposes leads to aerobic (oxygen-rich) conditions and the microbial activity oxidizes the carbon in the peat soil causing carbon loss in the form of gaseous CO_2 flux from the soil to the atmosphere. Since drainage must be regularly adapted to new levels for the rooting system requirements of the cultivated species, the loss in soil substance of drained histosols is irreversible and permanent until the peat deposit ultimately disappears (Fig. 2).

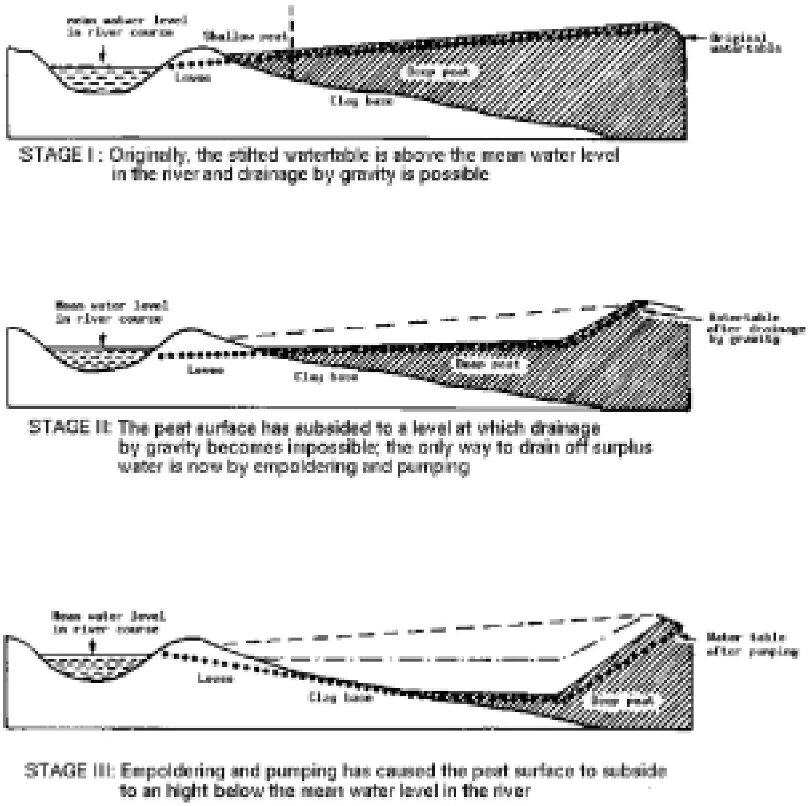

Fig. 2 – Possible stages in peat subsidence after drainage.

Experimental field [Deverel and Rojstaczer, 1996; Clair at al., 2002] and laboratory [Moore and Dalva, 1997] studies have demonstrated that the rate of CO_2 production from organic soils, and hence of related land sinking, primarily depends on peat composition and two hydrologic variables: soil temperature and moisture. Soil microbial activity generally doubles for each 10°C increase in temperature above 5°C and it has been established that in general CO_2 fluxes are much influenced by the depth of drainage, the higher the water table the lower the soil loss.

Agricultural lands located in the south-eastern part of the Veneto Region are characterized by the presence of soils with high organic content. Their drainage started soon after the reclamation and caused an adverse effect on the stability of those areas, with large subsidence rates that lead the zone to lie almost entirely below mean sea level (down to –4 m a.s.l.). Land settlement of several tens of centimeters recorded up to now and subsidence that will likely occur in the years to come constitute a serious problem for a sustainable development of this area in the near future. Pumping of agricultural drainage into waterways will become more and more expensive, with the reclamation authorities that in some cases may be forced to lower the pumping station elevation. Also saltwater intrusion from the adjacent Adriatic Sea, at present localized over a few zones, could become a widespread phenomenon to take care of.

In 2001 a research project (VOSS – Venice Organic Soil Subsidence) was initiated to study the process. The end goal is the development of a modeling tool for the prediction of this type of land subsidence to be effectively used in the agricultural practices and management strategies for the farmland south of the Venice Lagoon. The model development and validation are supported by extensive laboratory and field experiments in a hydrologically closed basin, the Zennare Basin, selected in the area of interest. At the moment of writing the project focused the two main issues: (1) hydrogeological characterization of the basin and (2) design and implementation of a field experiment for the determination of the most important parameters to be used in the modeling effort. This paper is mainly concerned with the description of the second issue.

After a brief description of the main hydro-geologic features of the study basin and an account of the observed land subsidence, the design of the field experiment and its implementation are presented and discussed.

2. *The Study Site.*

The Zennare Basin (45° 10' E and 12° 9' N) is an area of about 23 km^2 located right south of the Venice Lagoon, approximately 10 km from the Adriatic Sea (Fig. 1b). The basin was occupied in the 19th century by swamps and was reclaimed about 70 years ago. At present it lies almost entirely below mean sea level, mostly between -2 and -4 m, except for a small part in its northern part [Fig. 2, Rizzetto et al., this issue], and is almost completely dedicated to cereal growing.

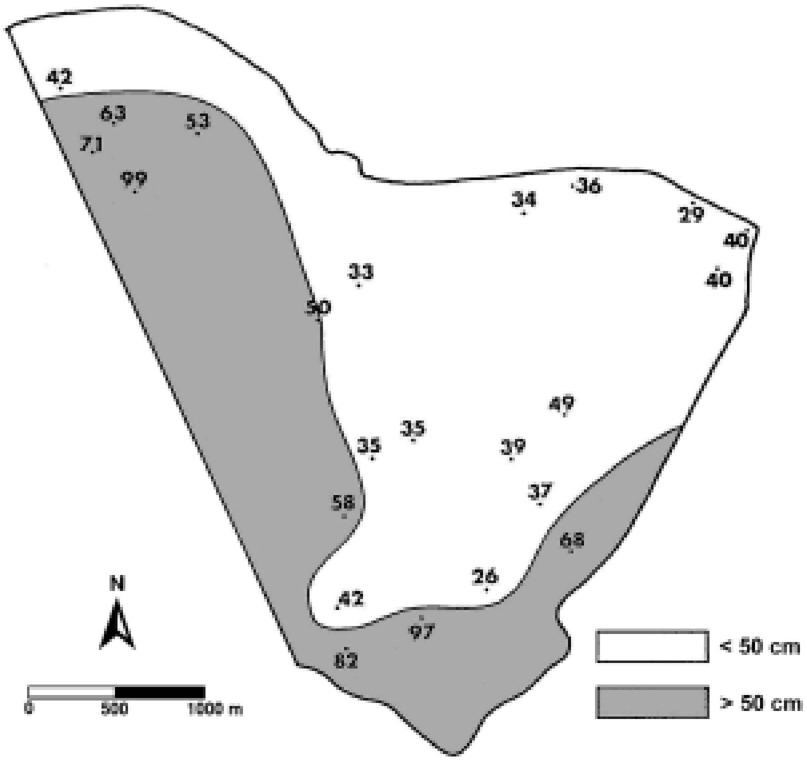

Fig. 3 – Estimate of land subsidence within the Zennare Basin between 1965 and 1983 (after Consorzio di Bonifica Adige-Bacchiglione [1996]).

Although an ad hoc monitoring campaign has never been made, the present critical ground elevation is due to land subsidence primarily caused by organic soil oxidation. An accurate measurement of the histosols sinking rates within the area is not available. However, land settlements ranging between 30 and 100 cm have been estimated between 1965 and 1983 by the reclamation authority [Consorzio di Bonifica Adige-Bacchiglione, 1996] with the aid of elevation maps of the area (Fig. 3). The average subsiding rate of 2.8 cm/year thus obtained provides an overall settlement of about 1.5 m over the last fifty years, that match pretty well with the protrusion of old hydraulic structures located within the basin and funded on the mineral soils underlying the outcropping peat layer (Figs. 4, 5). The fact that the loss of mass from peat soils might be the major subsidence process affecting this area is somehow confirmed by

Fig. 4 – Effects of land subsidence in the Zennare Basin: an old abandoned weir originally constructed to close a drainage ditch completely protruded above the ground level. A qualitative position of the ditch section in the original configuration is sketched.

Fig. 5 – The effect of land subsidence in the Zennare Basin: an old masonry culvert presently above the water level and substituted by two lower concrete drainpipes, the higher of which already unusable. A qualitative position of the ditch section in the original configuration is sketched.

the significantly smaller displacement rates (less than 1 cm/year) measured by high precision leveling surveys since the end of the 19th century by IGM (Military Geographic Institute) and CNR (National Research Council) along a leveling line adjacent to the study basin and running along the embankments of the Venice Lagoon margin where oxidation of organic soils is precluded [Tosi et al., 2000].

From the lithologic point of view, boreholes drilled down to –15 m from the ground surface [Gatti et al., this issue], geophysical investigations [Francese et al., this issue], field surveys, and aerial photograph interpretation [Rizzetto et al., this issue] carried out during the first year of the project have allowed the identification of the main geologic features of the area. A top peat layer between 1 and 1.5 m thick is nowadays uniformly present in the southern and central parts of the basin and is underlain by an alternation of sandy, silty, and clayey deposits with a few thin (few centimeters) intervening peat layers. The mineral sediments outcrop in the northern basin and constitute an almost impermeable aquiclude for the organic layer. The upper 40 cm of peat soil consists of ploughed and oxidized organic matter below which a fibrous peat usually with well-preserved fibres of *Phragmite australis* in growing position is found [Gatti et al., this issue]. The peat deposit is intersected by two paleo-river bed systems and a few small paleo-channels [Rizzetto et al., this issue; Francese et al., this issue].

The basin is hydrologically well defined (Fig. 1b). It is bounded southeastward by the embankment of the Cuori channel (B-C alignment, Fig. 1b) with water level as regulated by the Ca' Bianca pumping station (Fig. 1b), ranging between 1 and 1.25 m below m.s.l.. Hence the channel water level is always at least 2 m above the surrounding cultivated plain. An impermeable boundary is represented northward by the bank of the provincial road n. 7 “Rebosola” running about 2 m above the ground elevation (A-B, Fig. 1b). The study area is limited at the west border by a ditch (C-A, Fig. 1b) directly connected to the Cuori channel through a siphon operated by the reclamation authority.

The drainage network is made from a small number of channels approximately 5 m large and 1.5 m deep connected to a fine system of small ditches that subdivide the basin into rectangular fields of about 30-50 $\times$ 200-500 m and control the depth of the water table. Two major waterways, the Magnana and the Gorizia channels, convey the drainage water to the Zennare pumping station that discharge the water into the Cuori channel. The lowering of the water level at the pumping station entry from 1930 also provides an estimate of land subsidence in agreement with the other available information.

3. *Experimental Methods.*

The Zennare Basin has been instrumented at the end of 2001 – beginning of 2002 in order to measure the hydrological and meteorological parameters on which peat oxidation depends and to record the land subsidence rate. A number of test sites have been established in order to perform an accurate global hydrological balance of the basin, based on the *a priori* knowledge that water outflow is concentrated at the Zennare pumping station and water recharge occurs as rainfall, concentrated sinks through three siphons located along the Cuori channel embankment (Fig. 1b) and distributed infiltration through the same bank.

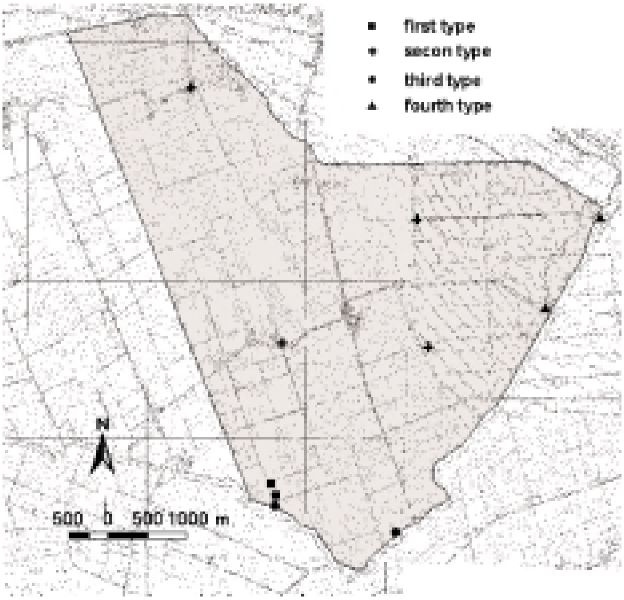

Fig. 6 – Location of the monitoring sites within the Zennare Basin.

Three types of monitoring sites have been planned and installed within the basin. Two principal test sites ("first type", Fig. 6) with an areal extent of 100 m^2, 200 m apart from each other, are established in the southern tip of the basin. Each site is permanently equipped with the following instruments (Fig. 7): *i*) a tilting bucket pluviometer with a sensitivity of 0.2 mm; *ii*) a non-directional anemometer with an accuracy of 0.25 m/s; *iii*) two piezometers, one located within the test site and the other close to the adjacent ditch, made from 3 m long PVC pipe of 2 inches diameter and instrumented with a pressure transducer characterized by a measuring range of 0 – 300 mbar and an accuracy of ±0.5 %FS; *iv*) five tensiometers to measure the capillary pressure, inserted 45° sloped so that the ceramic cups are located along the same vertical line with a 15 cm depth interval down to 75 cm (Fig. 8); the measurement range of the electronic pressure sensor is 0 – -950 mbar with an accuracy of ±0.5 %FS; *v*) five three-wire time domain reflectometry (TDR) 15 cm long probes for soil moisture content inserted horizontally along the same vertical and at the same depth as the tensiometers (Fig. 9); and *vi*) four soil temperature sensors at 1, 5, 15, and 30 cm depths with a measurement range between -15°C and 50°C (Fig. 9), plus one other 1 m deep sensor in the southern site. As suggested by Deverel and Rojstaczer [1996], ground surface displacement at each site is monitored by three displacement transducers characterized by a measurement range of 0 – 25 mm and an accuracy of ±0.5 %FS. The transducer body is attached at one end to a steel tripod anchored on three piles set into the ground to a depth of 11-12 m where an over-consolidated layer is located. The other end is connected to the land surface through a 0.5 cm thick, 10×10 cm aluminum plate resting on the soil (Fig. 10). The triangular steel structure, with sides of approximately 2 m, has been designed so to be as light as possible but with a negligible deformation compared to the expected subsidence rate when loaded with the force exerted by the displacement transducers (2.5 kg each) and by a 40°C thermal excursion.

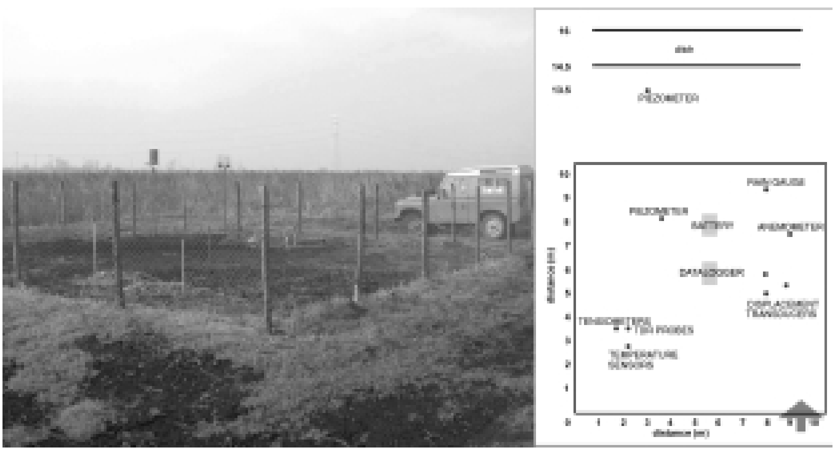

Fig. 7 – A principal test site established in the Zennare Basin with a schematic illustration of the instrument distribution.

Fig. 8 – Tensiometer location within a test site.

Except for the TDR probes, all sensors are connected to a datalogger (TER GEOLOG) with the electric power supplied by a single 12 volts rechargeable battery with an electrical capacity of 260 Ah that ensures about 1 month of continuous functioning at a hourly sampling rate. TDR probes will be connected in a near future through a multiplexer to an independent acquisition system. To avoid vandalisms and thefts, all the electric connections are sealed underground, with the datalogger and the battery buried inside waterproof IP68 cases. Since cultivation practices affect the soil peat structure and its characteristics in relation to the water-oxygen fluxes, the soil around the displacement transducers, the tensiometers and the TDR probes is managed so as to reproduce the actual conditions of the cultivated fields. At the end of the site installation a system of boardwalks is established to allow access without disturbing the soil surface.

Four other monitoring sites (“second type”, Fig. 6) are installed in the basin, also outside the zone characterized by the presence of outcropping organic soils, with the aim at providing useful information on the basin hydrological balance. In each station a rain gauge and a piezometer of the same type as those used in the principal sites are installed and connected to a small datalogger (TER AC420). The energy is supplied by a small 12 volts 12 Ah rechargeable battery lasting a couple of weeks, depending on rainfall intensity. The electric wires and the datalogger are buried into the ground.

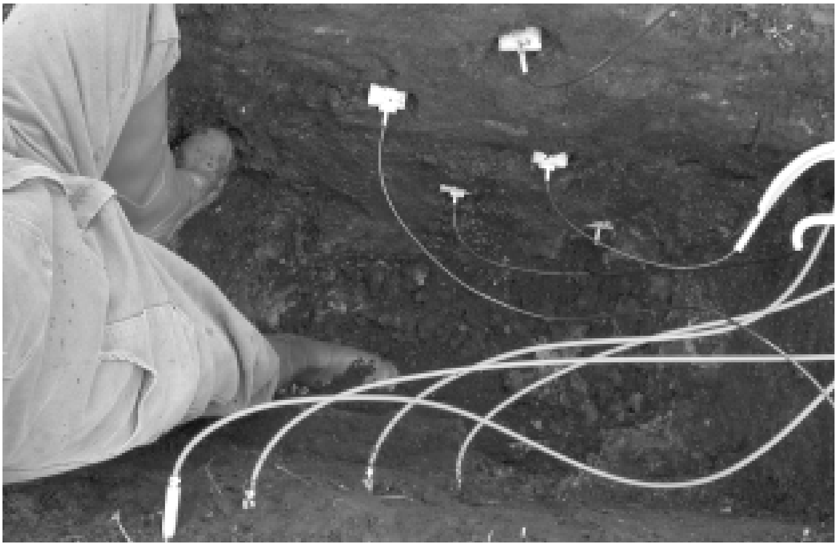

Fig. 9 – TDR probes (upper) and temperature sensors (lower) soon after their establishment.

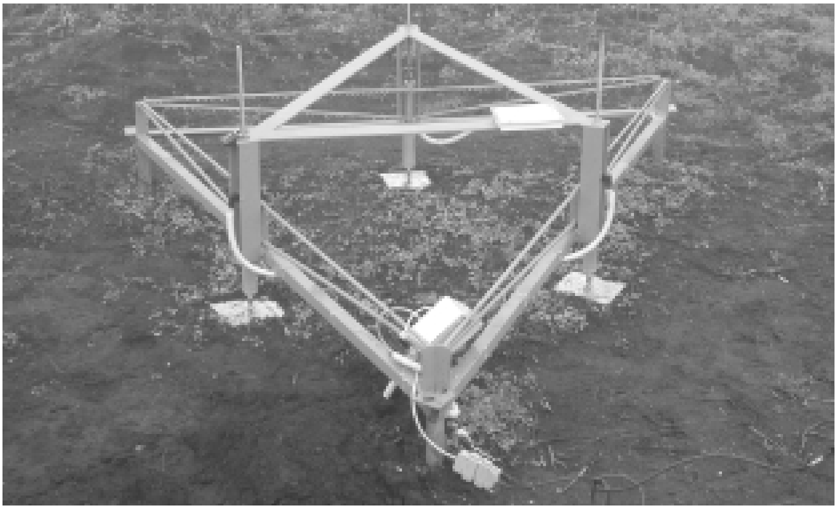

Fig. 10 – Steel tripod constructed to continuously monitor the ground elevation changes in the test field.

A third type of surveying site (Fig. 6) is established at two locations at the base of the Cuori channel embankment where a 2 m deep well is equipped with a water level transducer, whose housing contains the pressure sensor, the datalogger, and the battery. The measurement of the aquifer water table depth and channel water level fluctuations, together with the embankment geometry, will be used for the estimation of the distributed recharge through the channel levee.

Finally, two other monitoring sites, managed directly by the reclamation authority, are located at the Zennare and Ca' Bianca pumping stations where rainfall and water levels at the inlet and outlet of the pumping system are continuously measured ("fourth type", Fig. 6).

Two independent approaches to quantify CO_2 peat – atmosphere exchange rates are planned to be used during the research project: *i*) a chamber method and *ii*) a micrometeorological technique. Chamber methods are pointwise monitoring tools that measure changes in the gas concentration within a bottomless container placed on the ground surface. The non-steady-state (NSS) chamber method [Hutchinson and Livinston, 2001] will be used to estimate the CO_2 flux, as emitted from the soil, using the rate of CO_2 concentration increase. A rigid stainless steel chamber with a planar 50×50 cm dimension and a 25 cm height has been constructed by Geotea S.r.l. and Pergeo S.r.l.. The chamber is equipped with a barometric pressure transducer to check and compensate for the air pressure difference within and outside the chamber, an infrared gas analyzer, and a sampling port to collect air samples for later analyses by a portable gas chromatograph. To reduce soil disturbance related to chamber insertion, a collar connecting the chamber to the soil is located few centimeters below the ground surface. One collar will be permanently installed in one of the principal test site, while a second one will be moved around the basin to control and possibly estimate the spatial variability of CO_2 fluxes.

At a larger scale (on the order of few thousands of m^2) a micrometeorological technique, known as the eddy covariance technique [Moncrieff et al., 1997], is planned for use. This is based on the simultaneous high-frequency (10-20 Hz) measurement at about 1 m above the ground surface of the wind components by a three-dimensional ultrasonic anemometer and CO_2 concentration by an infrared analyzer (Fig. 11). The micrometeorological measurements will be carried out in a central basin position where a clear, flat fetch of several hundreds of meters is available to the north-east, the most frequent wind direction.

Fig. 11 – The micrometeorological instrumentation for the eddy covariance measurement during a first application period in the Zennare Basin.

5. *Conclusions.*

The Zennare Basin has been equipped in order to monitor the process of land subsidence caused by biochemical oxidation of organic soils. A number of sensors continuously record rainfall, wind speed, soil temperature and moisture, capillary pressure, and water table depth at different locations within the basin. An *ad hoc* extensometric apparatus has been designed and set up to directly measure the peat surface displacements. The CO_2 fluxes are designed to be recorded in a near feature over two distinct spatial scales, from chambers ($\approx$0.3 m^2) to patch ($\approx$1000 m^2).

The field experiment has been designed with a redundant number of sensors for each instrument type to avoid gaps in the data. Moreover, the high variability of rainfall characterizing the summer season has suggested the use of several pluviometers.

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