ESTIMATING PRIMARY AND SECONDARY SUBSIDENCE IN AN ORGANIC SOIL 15, 20, AND 30 YEARS AFTER DRAINAGE

Abstract: Wetland hydrology is being restored to Juniper Bay, a drained Carolina bay wetland in Robeson County, North Carolina that was drained for agriculture 30 years ago. It was hypothesized that the surface of the original water table could be estimated from the elevation of the organic soils before subsidence. No elevation data existed prior to drainage so a method of estimating the amounts of primary and secondary subsidence in organic soil was developed. The method to estimate primary subsidence was based on changes in bulk density as water is removed and the soil settles. Secondary subsidence was estimated from accumulation of a stable soil constituent (sand percentage) in the surface horizon and changes in bulk density as the soil oxidizes. Total subsidence was the sum of secondary and primary subsidence. Bulk density, particle size data, and organic carbon data were gathered from locations in Juniper bay and three undrained Carolina bays. Juniper Bay was drained with a network of ditches in three stages, 15, 20, and 30 years ago. The average total subsidence was 75, 77, and 86 cm after 15, 20, and 30 years of drainage. The proportions of primary and secondary subsidence were approximately equal. It was expected that primary subsidence would have been a higher proportions of the total subsidence however; the occurrence of fire would have increased the amount estimated for secondary subsidence. The average primary subsidence was estimated to be 34, 43, and 41 cm after 15, 20, and 30 years of drainage, with a secondary subsidence of 41, 33, and 46 cm. The average rate of primary subsidence was 3.9 cm yr^{-1}, and an average rate of secondary subsidence of 2.0 cm yr^{-1}. Subsidence values were variable across Juniper bay and the amount of subsidence was not

related to location at the crest of a field or near a ditch. Restoration of the hydrology in Juniper Bay to pre-drainage water table elevations could result in a water table that is above the soil surface, which does not meet the criteria for a successful restoration.

INTRODUCTION

Organic soils form by the accumulation of plant debris under anaerobic conditions. Most organic soils occur in areas that are saturated for much of the year, because the saturation maintains an anaerobic condition that retards decomposition (Everett, 1983). Glaz (1995) suggested that annual durations of saturation required for organic soil accumulation range from 15 to 94%. Once drained for agriculture, the surface of an organic soil decreases in elevation over time. Processes responsible for decrease include both primary subsidence and secondary subsidence (Everett, 1983). As shown in Fig. 3.1, primary subsidence is a relatively rapid process that results from a loss of buoyant force that causes the soil to sink under its own weight. Secondary subsidence is slower and is caused by decomposition of the organic debris as well as shrinkage.

Studies of organic soil subsidence have shown that the rates of primary and secondary subsidence are related to the original thickness of the soil, depth to water table (Stephens, 1956), mineral content (Slusher et al., 1974), temperature, precipitation, and management practices (Shih et al., 1998). Subsidence has been determined using benchmarks and surveying techniques before and after drainage has occurred (Stephens, 1954; Shih et al., 1998; Millette, 1976). Mathur et al. (1982) conducted an in-depth analysis of organic deposits from drained and undrained areas to establish a time sequence through the soil pedon with pollen at each location. Unique pollen types or elevated levels of pollen seen in all locations were used as chronological markers. The differences in the depths of the chronological markers were then used to estimate subsidence. They found that the rate of subsidence to be 6 cm yr^{-1} after 5 years and 3.67 cm yr^{-1} after 15 years. This method includes the effect of clearing in addition to settling and oxidation, and there is no way to separate primary and secondary subsidence. In addition a thorough knowledge of pollen analysis would be required. Dolman and Buol (1967) estimated subsidence in an area in North Carolina that was drained for 50 years but not farmed to be 57.5 cm or 1.2 cm yr^{-1} using the "one third thickness loss upon drying rule," i.e. subsidence is estimated to be one third of the original thickness. They extrapolated this over nearby agricultural areas and found that estimated subsidence rates ranged from 1.8 to 3.54 cm yr^{-1}, based on depth to mineral layer, with the shallower organic having the higher rate. This method is crude and cannot account for fire.

Several methods have been developed to control subsidence through water and land management. Levesque and Mathur (1984) have shown that additions of copper reduce the rate of subsidence by inhibiting soil enzymes that control the rate of oxidation of organic matter. Covering the surface with mineral material to slow diffusion of oxygen has also been tried with some success (Slusher et al., 1974). Keeping the amount of water in the peat to less than 50% or greater than 80% can slow decomposition (Stephens, 1956). Maintaining a high water table also reduces subsidence (Shih et al., 1998). Brooks and Lowe (1984) predicted that saturation for 60% of the year would slow subsidence of the soils of the Upper St. Johns River in Florida.

Wetland restoration projects frequently plug the ditches of drained agricultural fields and plant trees to recreate original conditions. In areas where organic soils have subsided, it is possible that ditch plugging will raise the level of groundwater above the soil surface. Fennema et al. (1994) predicted that the Everglades Agricultural Area (EAA) would be flooded for up to 360 days a year if man-made structures were removed, because the present surface elevation is 1.5 m below the original elevation. In extreme cases this may kill the newly planted vegetation before it has become established. We hypothesized that if the amount of subsidence could be estimated before ditches were plugged, then the potential problem of too great a water table rise following plugging might be avoided.

Estimating the amount of subsidence that has occurred will vary from site to site because it depends on average water table depth, soil temperature, and also on historical land treatments that were used to prepare the land for agriculture. Such treatments include, in addition to drainage, tree removal, crowning of fields, and stockpiling and burning debris (Lilly, 1981). The objective of this work was to estimate the level of primary and secondary subsidence that occurred in an organic soil following drainage and agricultural use at selected points across the organic soil.

MATERIALS AND METHODS

Theory and Assumptions

A hypothetical organic soil profile that has undergone both primary and secondary subsidence has two distinctly different organic soil horizons (Fig. 3.2). An Oap horizon has been plowed for agriculture and its strong granular soil structure results from shrinkage, oxidation, and tillage. Drying and shrinkage creates soil structure in the form of well-defined aggregates separated by large cracks (Pons and Zonneveld, 1965 and Lee and Manoch, 1974). This layer is black in color, which apparently results from oxidation of organic materials. The underlying Oa horizon is below the tillage zone. It has a massive soil structure and shows no evidence of shrinkage and drying. It may have a redder color than that of the Oap horizon, and is massive in structure because no shrinkage occurred to create cracks. The Cg horizon is mineral soil material and is not of interest in this study.

We assumed that the Oa horizon in Juniper Bay experienced primary subsidence but minimal secondary subsidence as evident by it's near massive structure. The Oap horizon was affected by both primary and secondary subsidence as evident by its strong granular structure. It was clearly within the depth of plowing and could be easily distinguished from the underlying organic material.

Method for Estimating Primary Subsidence

Primary subsidence occurs following drainage when the organic material settles under its own weight and compresses (Fig. 3.3). Volume is reduced by a reduction of pore space. There is no loss of organic material. The thickness of the organic soil layer decreases as it subsides causing bulk density to increase. This change in bulk density before and after drainage can be used to calculate the change in thickness of the organic soil material as a result of primary subsidence.

Loss through primary subsidence was estimated for a volume of organic soil that had a unit cross-sectional area and a height that included the entire thickness of the organic soil material. The volume of the original organic soil (V_o) was computed as:

$$V_o = T_o\ (\ 1\text{cm}^2) \tag{1}$$

where T_o is the thickness of the original organic soil material. The volume of the existing soil (V_{ps}) after primary subsidence was computed as:

$$V_{ps} = T_{ps}\ (1\text{cm}^2) \tag{2}$$

The mass of the organic soil material before primary subsidence (M_o) was equal to the mass of the soil after primary subsidence (M_{ps}). The reduction in volume following primary subsidence occurred only by a decrease in the thickness of the original soil volume (T_o). The cross-sectional area of the soil does not changed during primary subsidence.

The bulk density of the original soil (D_o) is computed as:

$$D_o = M_o / V_o = M_o /(T_o (1\text{cm} \times 1\text{cm})) \tag{3}$$

The bulk density for the soil after primary subsidence is computed as:

$$D_{ps} = M_{ps} / V_{ps} = M_{ps} / (T_{ps} (1\text{cm} \times 1\text{cm})) \tag{4}$$

The ratio of D_{ps} and D_o is related to the ratio of the thickness of the soil layers:

$$D_{ps} / D_o = [M_{ps} / T_{ps} (1\text{cm} \times 1\text{cm})] / [M_o / T_o (1\text{cm} \times 1\text{cm})] = T_o / T_{ps} \tag{5}$$

because we assumed that $M_{ps} = M_o$. The thickness of the original organic soil material (T_o) can be estimated as:

$$T_o = T_{ps} [D_{ps} / D_o] \tag{6}$$

This gives us the original thickness of the organic soil. The amount of primary subsidence (S_{ps}) that has occurred is the difference between the thickness.

$$S_{ps} = T_o - T_{ps} \tag{7}$$

We evaluate similar organic types of soils, e.g., sapric, between the original soil and the soil after primary subsidence because of the inherent difference in bulk density between fibric, histic, and sapric material. In making these calculations, we assume that the sapric material in the profile subsides to a uniform bulk density. To make this calculation we measured D_{ps} and T_{ps} in the organic soil that has subsided. A value for D_o was obtained by sampling undrained organic soil that contains natural vegetation.

Method for Estimating Secondary Subsidence

While organic soils form by the accumulation of organic materials, they usually contain small amounts of sand and silt deposited by wind and water. The sand and silt consist primarily of quartz, which is a mineral that does not weather or alter over short time periods of less than 1000 years or so (Buol et al., 2003). Sand particles found in the organic material will be used in estimating secondary subsidence, while changes in bulk density will be used in calculating primary subsidence. Changes in subsidence of an organic soil following drainage will be discussed using a volume of undrained soil that has a cross sectional area of 1 cm^2. It is assumed that this area remains constant during subsidence, and the volume decrease occurs only through a decrease in thickness.

We used a method described by Brewer (1976) to estimate the amount of secondary subsidence. Brewer (1976) estimated the soil volume lost when primary minerals weather. While he applied the technique for the weathering of mineral materials, we adapted it for the decomposition of organic material. Two soil volumes must be compared, the parent material or unoxidized organic soil (V_{pm}), and a volume of oxidized soil (V_s). As the parent material weathers it loses both volume and mass. Some crystalline minerals dissolve, some turn to clay, but some resist weathering and remain unchanged. As weathering proceeds, the resistant minerals increase in concentration relative to the concentration in the original material (Fig. 3.4). This relationship is described as:

$$V_s D_s R_s = V_{pm} D_{pm} R_{pm} \tag{8}$$

where V_s = volume of present day soil

D_s = bulk density of present day soil horizon,

R_s= percentage by weight of the stable constituent in present day soil horizon,

V_{pm}= volume of parent material from which soil was derived,

D_{pm} = bulk density of parent material, and

R_{pm}= percentage by weight of the stable constituent in the parent material.

Changes in the thickness of a horizon can be calculated by assuming that the change in volume through weathering occurs only in the vertical dimension and the cross-sectional area of the soil remains constant. When a soil mass shrinks, it appears that the shrinkage occurs in all dimensions, however, in the horizontal dimension the shrinkage creates voids, and these voids are part of the soil volume (Fig. 3.5). As a result, the soil's cross-sectional area is remains constant throughout the weathering process because solid material is replaced by voids. The voids can be filled by the rearrangement of soil aggregates or particles. The change in volume that occurs through secondary subsidence occurs through a decrease in the thickness of the soil horizon (T_s):

$$V_s = T_s\,(1\text{cm}^2) \tag{9}$$

and the same can be said for V_{pm} and thickness of the original parent material (T_{pm}). Equation 8 can then be arranged to calculate T_{pm}.

$$T_{pm} = T_s \times (D_s R_s / D_{pm} R_{pm}) \tag{10}$$

Secondary subsidence (S_s) would be equal to the difference in the thickness of the parent horizon and the present soil horizon.

$$S_s = T_{pm} - T_s \tag{11}$$

We used the underlying sapric material, which has undergone primary subsidence only, as the parent material and used the percent sand in the organic soil as the stable constituent. We assumed that the current surface horizons formed from material similar to that of the underlying sapric material. We also assumed that the water table has been maintained at a level to prevent a significant loss of the parent material due to oxidization. We realize that there are many environmental, vegetative, and meteorological situations that factor into the deposition of sand into the organic material. However, we assume that over time, sand that is deposited through erosion or wind would be relatively constant and would result in a relatively constant distribution through the profile. Sand deposition that is deposited episodically would be homogenized through the profile over time by tree throw and bioturbation. We feel that such an assumption is valid after examining sand percentages through organic profiles in natural Carolina bays. Sand percentages varied by less than 5% through the sapric part of the organic profiles.

Sample Calculations for Primary Subsidence

Data from one location in the drained Carolina bay (Table 3.1) will be used to illustrate the calculations. D_o from samples from the organic sapric soils in the natural bays and found it to be 0.25 g cm^{-3}. The D_{ps} from the subsided soils was determined to be 0.45 g cm^{-3} in the Oa4 horizon. We also chose the lowest bulk density since we assume any difference in bulk density greater than the lowest is due to secondary subsidence. T_{ps} is equal to the depth, from the surface, of the horizon with the lowest bulk density. Horizon Oa4 extends to a depth of 66cm. Therefore, using equation 4:

$$T_o = 66 \text{ cm} [0.45 \text{ g cm}^{-3} / 0.25 \text{ g cm}^{-3}] = 119 \text{ cm}$$

$$S_p = 119 \text{ cm} - 66 \text{ cm} = 53 \text{ cm}$$

This gives us an original thickness of 119 cm and a primary subsidence of 53 cm. The length of time for primary subsidence to occur varies, and since we have no data to suggest how long it took for primary subsidence to occur, we chose 10 years. This would give us a primary subsidence rate of 5.3 cm yr^{-1} during the first 10 years.

Sample Calculations for Secondary Subsidence

Using the data in Table 3.1 for calculating secondary subsidence, the organic horizon that had the lowest sand percentage was determined to be the “parent” horizon from which the horizons above were formed. For the example, the Oa4 horizon is the parent material, and Oa3 is the soil material. The change in thickness has to be calculated for each horizon above the parent horizon and then summed to determine total subsidence. Using equation 10 for the Oa3 horizon:

$$T_{pm} = T_s \text{ x } (D_sR_s) / (D_{pm}R_{pm})$$

$$T_{pm} = 20 \text{ cm x } (0.45 \text{ g cm}^{-3} \text{ x } 9.96) / (0.45 \text{ g cm}^{-3} \text{ x } 5.84)$$

$$S_s = 34.1 \text{ cm} - 20 \text{ cm} = 14.1 \text{ cm}$$

This gives us 14.1 cm of secondary subsidence in the Oa3 horizon. This was repeated for the Oa2 and Oa1 horizons, using the same parent material. The change in depth for Oa1 is 44 cm and 30 cm for Oa2 for a total amount of secondary subsidence of 74 cm. To obtain the rate of secondary subsidence, the amount of secondary subsidence was divided by the amount of time since drainage started. This sampling area has been drained for 30 years for an average secondary subsidence rate of 2.9 cm year^{-1}.

This method did not work for locations in which the lowest amount of sand was in the surface horizon. This resulted in negative values of subsidence, which meant that there was an accumulation of material. Also, if sand content in soil horizons (R_s) was more than three times the sand contents in the parent horizons (R_{pm}), it was assumed that the soil horizon was fill material and therefore that soil horizon was not used in the calculations. In addition to using total sand for the secondary subsidence calculations, the coarse and fine fractions of sand were evaluated, and we found that using total sand gave an estimate that was in between the two sand fractions.

Sampling Locations and Laboratory Analysis

Juniper bay is a 256 ha Carolina bay southeast of Lumberton, North Carolina that was drained and placed into agricultural production ($34^{o}30'30''N$ $79^{o}01'30''E$). The Robeson County soil survey (McCachren, 1978) showed that approximately 60% of the Juniper Bay consisted of organic soils that were classified as members of the Ponzer series (Loamy, mixed, dysic, thermic Terric Haplosaprists). Organic soil layers in these soils range from 40 to 130 cm. Undrained organic horizons have a massive soil structure, but develop subangular blocky or granular structure following drainage (official series description). Plant communities believed to have been present in Juniper Bay included a Nonriverine swamp forest, High pocosin, and Peatland Atlantic White Cedar forest communities as described by Schafale and Weakly (1990).

Aerial photographs and interviews with previous landowners were used to establish the drainage history of Juniper Bay. Approximately one third was drained in 1971, another third drained in 1981, and the last third drained in 1986. Drainage ditches were dug to depths of 1m in most of the Bay, but these fed into larger ditches that extended to depths of approximately 4 m. Field "cuts" were the land areas surrounded by ditches on all sides, which were used for agriculture. At selected field cuts, paired sampling points, one at the crest and one near a ditch, were placed at locations determined by an equilateral triangle grid randomly placed across the site. Pits were dug to a depth of approximately 1 m using a backhoe. In each pit, the soil profile was described to determine depth, color, and structure of major soil horizons. Uhland cores were taken from each horizon to determine bulk density. Bulk samples were taken from each horizon described in the profile. Total organic carbon was determined through dry combustion with a Perkin-Elmer PE2400 CHN

Elemental Analyzer (Culmo, 1988). Particle size was determined at the University of Georgia, Soil Analysis Lab in Athens, GA., with the pipette method on a 10 g sample, and sand size by sieving. Samples were prepared for particle size analysis by first oxidizing the organic matter with concentrated (30%) hydrogen peroxide. The amount of mineral material in the initial 10 g sample was determined with an additional 10 g sample that was placed in a muffle furnace at 400^{o}C for 24 hours to remove organic matter, leaving the mineral material. Percent sand from the total sample was calculated by multiplying the percent sand from the particle size analysis by the mass of the mineral material and then dividing by the mass of the original sample.

Three natural undrained Carolina bays in Bladen County, North Carolina, Tatum Millpond Bay (34^{o}43’00”N 78^{o}33’00”E), Charlie Long Millpond Bay (34^{o}46’00”N 78^{o}33’30”E), and Causeway Bay (34^{o}39’45”N 78^{o}25’45”E), were selected for comparison. These natural bays had 60-100% of organic soils that are classified as a Pamlico series (Sandy or sandy-skeletal, siliceous, dysic, thermic Terric Medisaprists) (Leab, 1990). These soils have organic material 40 to 130 cm thick and are underlain by sand. Plant communities found in these bays were Pond Pine Woodland, Non-riverine Swamp Forest, Bay Forest, and High Pocosin, as described by Schafale and Weakly (1990).

Trails were cut through dense vegetation into the natural bays to reach sampling locations. Soil profiles at four locations in the organic soils of each bay were described using a McCauley peat sampler. Bulk samples were taken from each horizon for carbon and particle size analysis. Bulk density was determined by taking a 10 cm undisturbed sample with the McCauley peat sampler.

RESULTS AND DISCUSSION

Figure 3.6 shows the locations of all sampling locations, and those that are organic, in Juniper Bay. The organic soils from Juniper Bay and the natural bays are classified as Terric Haplosaprist with <40 cm organic material. Typical profile descriptions are shown in Table 3.2, and selected physical and chemical properties are shown in Table 3.3. The undrained organic soils had a surface Oi and Oe horizon that was 50 cm thick, while these horizons were absent in the drained Carolina bay. The Oa horizons in the undrained bay had massive structure, while the drained Carolina bay had strong granular structure in the surface Oap horizon as a result of tillage and dessication. In some sites, very coarse prismatic to subangular blocky structure had developed. The Oa horizons in the drained bay were very dark brown (10YR 2/2) sapric muck compared to the black (10YR 2/1) sapric muck of the undrained bays. The organic horizons were thicker, 170 cm, in the undrained bay, compared to 52 cm in the drained bay. Bulk density and sand content were two to three times higher in the organic horizons of the drained bay. The difference in bulk density and changes in structure between the drained and undrained bays demonstrated primary subsidence. The amount of sand in the organic soils of the drained bay was higher at the surface and decreased with depth, while the amount of sand in the Oa horizons of the undrained bay relatively constant. This trend in sand is what we expected to see in areas where secondary subsidence occurred. Not all organic soil locations were used, specifically if the lowest sand percentage was in the surface horizon or if there was no Oa horizon that could be used as parent material. The locations that were chosen are in Table 3.4. Since the initial study on Juniper Bay was not designed for determining subsidence of organic soils, we were unable to develop a statistical analysis. Therefore, data consists of actual calculated estimates and averages.

Total subsidence varied among locations (Table 3.4) and with time since drainage. Averages of the total subsidence values across the three time periods show that the organic soils subsided approximately 80 cm. Subsidence in the fields drained for 15 years is slightly less, 75.0 cm, than for fields drained for 20 or 30 years, 76.6 cm and 86.4 cm, respectively. This trend of total subsidence indicates that the longer a site is drained, the greater the amount of subsidence.

Estimated rates of primary and secondary subsidence vary across locations (Table 3.4). The average rate of primary subsidence is 3.9 cm yr^{-1}. Primary subsidence rates were lowest in the areas drained for 15 years, 3.4 cm yr^{-1}, and were highest in the areas drained for 20 years 4.3 cm yr^{-1}. This is probably because the water table in the area drained 15 years ago is closer to the surface than in the other areas, maintaining buoyancy over more of the profile. Shih et al. (1998), showed that the rate of subsidence in the Everglades Agricultural Area has decreased from 2.5 to 3.0 cm yr^{-1} during the years 1913 to 1978, to 1.45 cm yr^{-1} during the years 1978 to 1997 as a result of better water management which raised the water table to slow decomposition. The average rate of secondary subsidence was approximately 2.0 cm yr^{-1} (Table 3.4). Secondary subsidence rates were highest after 15 years of drainage, 2.8 cm yr^{-1}, and similar after 20 and 30 years of drainage, 1.7 and 1.5 cm yr^{-1} respectively.

These estimates of subsidence and subsidence rate are relatively consistent with other reported subsidence rates. Stephens (1956) reported a subsidence rate of 4.3 cm yr^{-1} over a 50-year period in Florida, Ireyresr (1963) reported a rate of 1.5 cm yr^{-1} over a 100-year period in England, and Jongedyk et al., (1950) reported a rate of 1.5 cm over 6 years in

Indiana. These calculated values are also similar to those found by Tant (1979) in North Carolina. A yearly loss of 1.2 cm was found on a Belhaven muck and 0.38 cm on a Pungo muck. Average annual subsidence in Quebec was 2.1 ± 0.4 cm yr^{-1} over 38 years (Millette, 1976), and subsidence in New Orleans ranges from 1 to 5 cm yr^{-1} (Slusher et al., 1974).

The proportion that primary subsidence comprised of the total subsidence varied widely (Table 3.4), but overall the average proportion of primary and secondary were approximately equal. The largest variations occurred in the area drained for 30 years where primary subsidence accounted for between 13 and 85% of total subsidence. This result was unexpected because it was thought that secondary subsidence was a slower process. Previous landowners indicated, however, that fire was used in the clearing process to remove tree debris during the clearing operation, and charcoal was found in soil profiles at Juniper Bay (Table 3.2). Fires also occurred naturally through lightning strikes. If a site burned shortly after drainage ditches were installed, it is possible that loss through secondary subsidence would exceed that of primary subsidence. Loss of the organic material through burning would concentrate sand, and also lessen the weight of the material compressing the parent material. This would keep the bulk density of the parent material low. Several studies have shown that subsidence tends to decrease with increasing distance from a ditch (Burke, 1963; Brandof, 1992), however, our estimates neither verified or contradicted their findings when comparisons were made between ditch and crest locations.

The results did not show greater subsidence near ditches as had been expected. There is a wide range of estimates for primary and secondary subsidence. This could be due to the ditches being shallow in most of the site. The land clearing process is also complex and involves the use of fire, ditch construction and maintenance, and crowning of fields.

Considering the variety of operations that are used to prepare and maintain the land in agriculture it is not surprising that we are unable to see a clear effect of the ditches on subsidence rates.

SUMMARY AND IMPLICATIONS

We realize that these values are estimates and that some assumptions may not hold for other sites. Some sample locations near ditches could have had the organic materials contaminated by ditch maintenance operations which brought subsurface material to the surface leading to increased sand at the surface which would result in increased estimates of secondary subsidence. Our assumption of constant sand deposition could be incorrect. Estimates for subsidence rates might be off because fires that have been known to occur may have resulted in most of the subsidence occurring during one event. However, we feel that for estimating secondary subsidence when there is no initial measurement of elevation, the assumptions are valid, and the data useful.

For the Carolina bay restoration project in question, if the drainage ditches were filled in the water table will rise to near the original surface of these organic soils. Our estimate is that the water would rise approximately 80 cm above the existing surface. The mineral soils around the edge of the Carolina bay are higher than the organic soils by approximately this amount. If all the ditches were plugged at the same time, the Carolina bay would probably develop a pond over the existing organic soils. This would probably prevent the re-establishment of the original vegetation.

Future studies that evaluate subsidence by these methods should include: a comprehensive sampling scheme for statistical analysis; detailed sampling of the soil profile at 15 cm depth intervals; and an improved method for measuring bulk density from undrained sites. A thorough evaluation of the assumptions regarding uniform sand distribution and the bulk density changes during subsidence needs to be done prior to computing subsidence. It is beneficial to use reference sites that show little disturbance, other than that associated with drainage and clearing, so that errors associated with additions of mineral material to the surface could be minimized or avoided. Future work might also include computing subsidence by estimating secondary subsidence first and then using that data to estimate primary subsidence.

REFERENCES

Brandof, K.L. 1992. Impact of ditching and road construction on Red Lake Peatland. p. 163-172. *In* H.E. Wright, Jr., B.A. Coffin, and N.E. Aaseng (ed.) The Patterned Peatlands of Minnesota. Univ. of Minnesota Press, Minneapolis.

Brewer, R. 1976. Fabric and Mineral Analysis of Soils. p. 63-87. Robert E. Krieger Publishing Company; Huntington NY.

Brooks, J.E., and E.F. Lowe. 1984. U.S. EPA clean lakes program, phase I. Diagnostic feasibility study of the Upper St. Johns River Chain of Lakes. Vol. II-feasibility study. Technical Publications SJ 84-15, St. Johns River Water Management District, Palatka, Florida.

Buol, S.W., R.J. Southard, R.C. Graham, P.A. McDaniel. 2003. Soil Genesis and Classification 5th ed. Iowa State Press. Ames, Iowa.

Burke, W. 1963. Drainage of blanket peat at Glenamory. p. 809-817. *In* Proceedings of the Second International Peat Congress, Leningrad, USSR.

Culmo, R.F. 1988. Principle of Operation – The Perkin-Elmer PE 2400 CHN Elemental Analyzer. Perkin Elmer Corp. Norwalk, CT.

Dolman, J.D., and S.W. Buol. 1967. A Study of Organic Soils (Histosols) In the Tidewater Region of North Carolina. North Carolina Ag. Ex. St. Tech. Bull. No. 181.

Everett, K.R. 1983. Histosols. p. 1-53. *In* L.P. Wilding, N.E. Smeck and G.F. Hall (eds.) Pedogensis and Soil Taxonomy II. The Soil Orders. Elsevier, Amsterdam.

Fennema, R.J., C.J. Neidrauer, R.A. Johnson, W.A. Perkins, and T.K. MacVicar. 1994. A computer model to simulate natural Everglades hydrology. *In* Davis, S.M., and J.C. Ogden (eds.), Everglades: The Ecosystem and its Restoration. St. Lucie Press, Delray Beach, Florida.

Glaz, B. 1995. Research seeking agricultural and ecological benefits in the Everglades. J. Soil Water Conserv. 50:609-613.

Ireyresr, 1963. Vegetation and Soils, A World Picture. p. 324. Aldine, Chicago.

Jongedyk, H.A., Hickok, R.B., Mayer, I.D. and N.K. Ellis, 1950. Subsidence of muck soils in northern Indiana. Purdue Univ. Agric., Exp. Sta., Spec. Circ., 366:1-10.

Leab, R.J. 1990. Soil Survey of Bladen County North Carolina. USDA-SCS. Washington D.C.

Lee, G.B. and B. Manoch. 1974. Macromorphology and Micromorphology of a Wisconsin Saprist. p.47-62 *In* M. Stelly and R.C. Dinauer (eds.) Histosols Their Characteristics, Classification and Use. SSSA pub 6. Soil Sci. Soc. Am. Madison, Wisconsin.

Levesque, M. P. and S.P. Mathur. 1984. The effect of using copper for mitigation Histosol subsidence on : 3. The yield and nutrition of minicarrots, carrots, and onions grown in Histosols, mineral sublayers, and their mixtures. Soil Sci. 138:127-137.

Lilly, J.P., 1981. The Blackland Soils of North Carolina: Their Characteristics and Management for Agriculture. p.27-33. North Carolina Ag. Res. Tech Bul. No. 270.

Mathur, S.P., M.P. Levesque, and P.J.H. Richard. 1982. The establishment of synchrony between subsurface layers and estimation of overall subsidence of cultivated organic soils by a palynological method. Can. J. Soil Sci. 62:427-431.

McCachren, C.M. 1978. Soil Survey of Robeson County North Carolina. USDA-SCS. Washington D.C.

Millette, J.A. 1976. Subsidence of an organic soil in southwestern Québec. Can. J. Soil. Sci. 56:499-500.

Pons, L.J. and I.S. Zonneveld. 1965. Soil Ripening and Soil Classification Initial Soil Formation in Alluvial Deposits and a Classification of the Resulting Soils. International Institute for Land Reclamation and Improvement pub 13. H.Veenman & Zonen N.V. Wageningen, Netherlands.

Schafale, M.P. and A.S. Weakley. 1990. Classification of the Natural Communities of North Carolina: Third Approximation. p. 205-217. North Carolina Natural Heritage Program, Division of Parks and Recreation, Department of Environment, Health and Natural Resources. Raleigh, NC.

Shih, S.F., B. Glaz, and R.E. Barnes, Jr. 1998. Subsidence of organic soils in the Everglades Agricultural Area during the past 19 years. Soil and Crop Sci. Soc. Florida. 57:20-29.

Slusher, D.F., W.L. Cockerham, and S.D. Matthews. 1974. Mapping and interpretation of Histosols and Hydraquents for urban development. p. 95-109. *In* A.R. Aandalh, S.W. Buol, D.E. Hill, and H.H. Bailey (eds.) Histosols; Their Characteristics, Classification, and Use. SSSA Special Pub 6. Soil Sci. Soc. Am. Inc., Madison, WI.

Stephens, J.C. 1956. Subsidence of organic soils in the Florida Everglades. Soil Sci. Soc. Am. Proc. 20:77-80.

Tant, P. 1979. Subsidence of organic soils. Soil Sci. Soc. N.C. Proc. 22:75-80.

Table 3.1. Values for sample subsidence calculations. Bulk density from Oa4 is used for estimating primary subsidence because it is the lowest. Horizon Oa4 is used as the parent material in estimating secondary subsidence because of the lowest % sand. All other horizons have a concentration of sand that could be attributed to secondary subsidence.

Horizon	**Horizon Thickness**	**Bulk Density**	**Sand**	**Change in horizon thickness**
	(cm)	(g cm^{-1})	(%total sample)	(cm)
Oa1	10	0.75	18.7	43.6
Oa2	10	0.75	13.9	12.7
Oa3	20	0.45	10.0	14.1
Oa4	26	0.45	5.8	**0 (parent material)**

Table 3.2. Typical profile from an organic soil at an undrained natural Carolina bay and from a drained Carolina bay.

Horizon	Depth	Description
	cm	
		Undrained
Oi	0-20	Black (10YR 2/1) fibric to hemic material; massive structure; gradual boundary; root and debris mat.
Oe	20-50	Very dark brown (7.5 YR 2.5/2) hemic material; massive structure; gradual boundary; organic bodies 0.5-1 cm; many roots and debris.
Oa1	50-82	Very dark brown (10YR 2/2) sapric material; massive structure; clear boundary; common large pieces of wood debris.
Oa2	82-107	Black (10YR 2/1) sapric material; massive structure; gradual boundary; few large pieces of wood debris.
Oa3	107-145	Black (10YR 2/1) sapric material; massive structure; gradual boundary.
OC	145-170	Black (10YR 2/1) sapric muck with <2% sand grains; massive structure; abrupt boundary.
C	170-190	Very dark brown (10 YR 2/2) sand; single grain structure.
		Drained
Oap	0-11	Black (N 2.5/0) sapric material; strong medium (2mm) granular structure; abrupt boundary.
Oa1	11-31	Very dark brown (10YR 2/2) sapric material with 10% wood fragments and 10% charcoal; massive structure; diffuse boundary.
Oa2	31-52	Very dark brown (10YR 2/2) sapric material with 10% wood fragments and 10% charcoal; massive structure; abrupt boundary.
Bw	52-61	Dark reddish brown (5YR 3/3) sandy loam; moderate coarse (5cm) prismatic structure; abrupt boundary.
BC	61-78	Yellowish brown (10YR 5/4) loamy sand with 40% white (2.5Y 8/1) sand in areas 1mm in diameter; there was 10% wood fragments; massive structure; clear boundary.

Table 3.2 continued

C1	78-100	Light yellowish brown (10YR 6/4) loamy sand with 5% wood Fragments; massive structure; clear boundary.
C2	100+	Dark gray (10YR 4/1) loamy sand; single grain structure. reaction to alpha, alpha; dense.

Table 3.3. Particle size, organic carbon, and bulk density of typical profiles from Juniper bay and undrained natural bays.

Horizon	Depth	OC	BD	Sand	Silt	Clay
	(cm)	(%)	g cm^{-3}	----------(%)----------		
			Drained			
Oap	0-11	26.25	**0.76**	34.2	14.3	10.3
Oa1	12-31	52.52	**0.47**	16.7	22.9	7.3
Oa2	32-52	27.91	**0.47**	41.1	18.1	7.8
Bw	53-61	5.46	**0.93**	74.0	8.5	9.6
BC	62-78	0.48	**1.55**	93.1	1.8	4.3
C1	79-100	0.26	**1.55**	91.3	2.5	5.9
C2	101-110	0.32	**---**	91.9	1.7	5.9
			Undrained			
Oi	0-20	41.25	---	---	---	---
Oe	21-50	37.37	---	---	---	---
Oa1	51-82	42.28	0.18	6.8	11.5	9.0
Oa2	83-107	34.74	0.21	14.0	17.3	10.0
Oa3	108-145	34.56	0.19	14.2	29.9	10.3
OC	146-170	16.35	0.49	46.1	20.4	6.8
C	190	---	0.87	78.7	12.1	1.7

Table 3.4. Estimated secondary subsidence from selected locations. The C or D in the sample location indicates if the sampling pit was at the crest (C) or near the ditch (D). Rate for secondary subsidence was calculated by dividing the amount of subsidence by the years of drainage. Primary subsidence rate was estimated by dividing the amount of subsidence by 10 years.

Plot Location	Primary subsidence		Secondary subsidence		Total subsidence		
	Amount	Rate	Amount	Rate	Absolute	Primary	Secondary
	(cm)	(cm/yr)	(cm)	(cm/yr)	(cm)	------ (%) -----	
			15 Years After Drainage				
66D*	13.9	1.4	42.3	2.8	56.2	25	75
68D	26.8	2.7	55.0	3.7	81.8	33	67
8D	60.2	6.0	26.8	1.8	87.0	69	31
Av.	**33.6**	**3.4**	**41.4**	**2.8**	**75.0**	**42**	**58**
			20 Years After Drainage				
10C*	24.4	2.4	50.0	2.5	74.4	32	68
16C	45.8	4.5	25.3	1.3	71.1	65	35
16D	54.3	5.4	45.2	2.3	99.5	54	46
6C*	72.0	7.2	23.6	1.2	95.6	75	25
11C	20.4	2.0	21.8	1.1	42.2	48	52
Av.	**43.4**	**4.3**	**33.2**	**1.7**	**76.6**	**57**	**43**
			30 Years After Drainage				
2D	33.6	3.3	6.2	0.2	39.8	84	16
4D	61.4	6.1	8.3	0.3	69.7	87	13
5C	52.8	5.2	85.9	2.8	138.7	43	57
5D	14.4	1.4	82.9	2.8	97.3	15	85
Av.	**40.6**	**4.0**	**45.8**	**1.5**	**86.4**	**47**	**53**

* Did not include surface horizons that had greater that three times R_{pm} in the calculation of secondary subsidence.

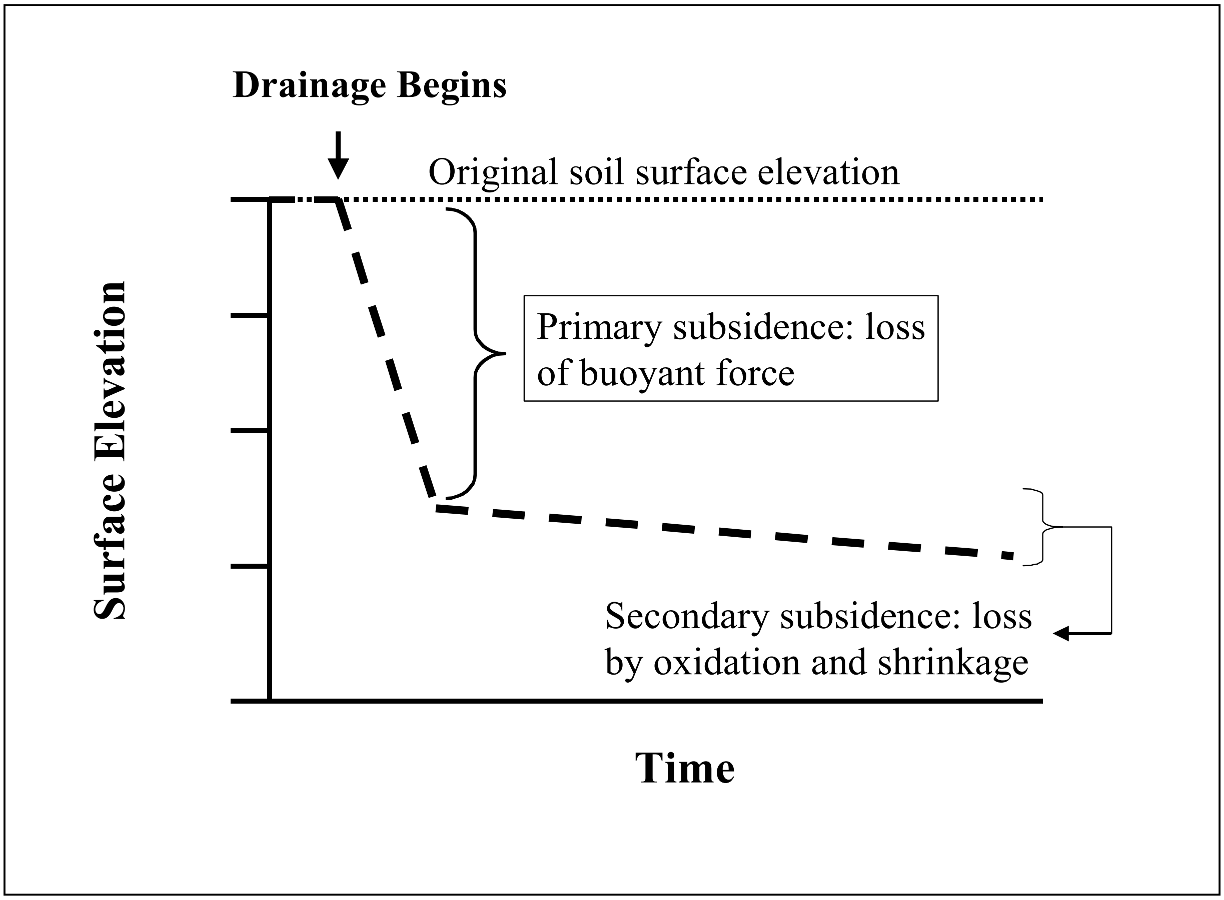

Fig. 3.1. Illustration of the hypothetical effects of subsidence on the decrease in elevation of an organic soil following drainage. Primary subsidence occurs quickly due to loss of water through drainage. Secondary subsidence is a slower process.

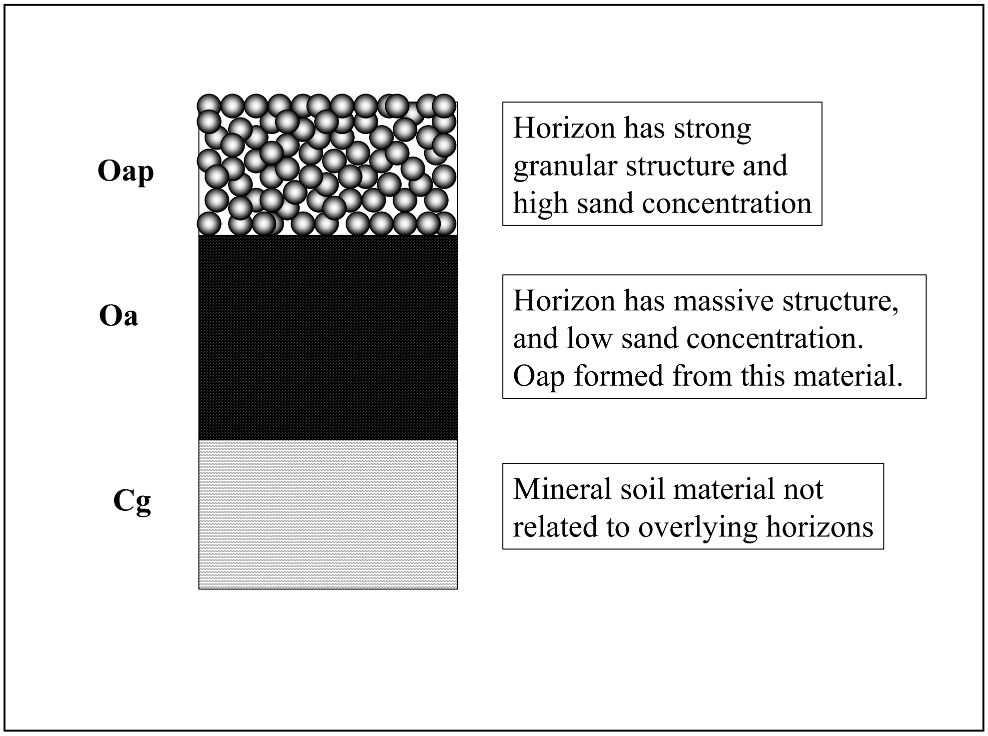

Fig. 3.2. Example of a soil profile consisting of organic soil material over mineral material. The Oap horizon is tilled and undergoes the most oxidation. The Oa horizon showed little influence of oxidation and was used as the parent material for the Oap horizon. The mineral material was not considered in the calculations.

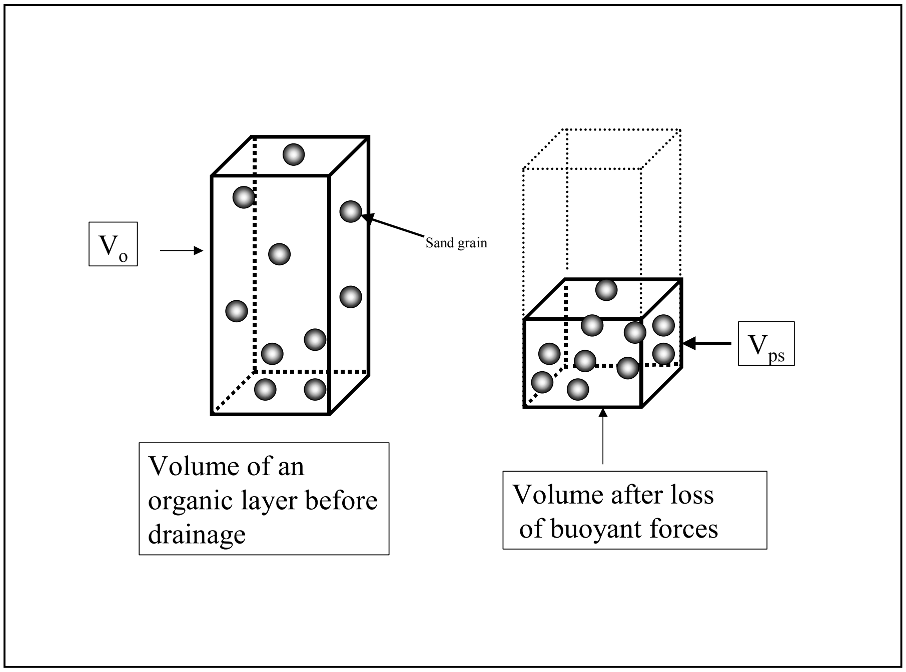

Fig. 3.3. Illustration of how primary subsidence reduces volume while the mass remains the same in an organic soil horizon following loss of buoyant forces. V_o is the volume of soil having a unit cross-section before primary subsidence occurs. V_{ps} is the volume of soil after primary subsidence, which also has a unit cross-sectional area. It is assumed that subsidence has only altered soil volume in the vertical direction.

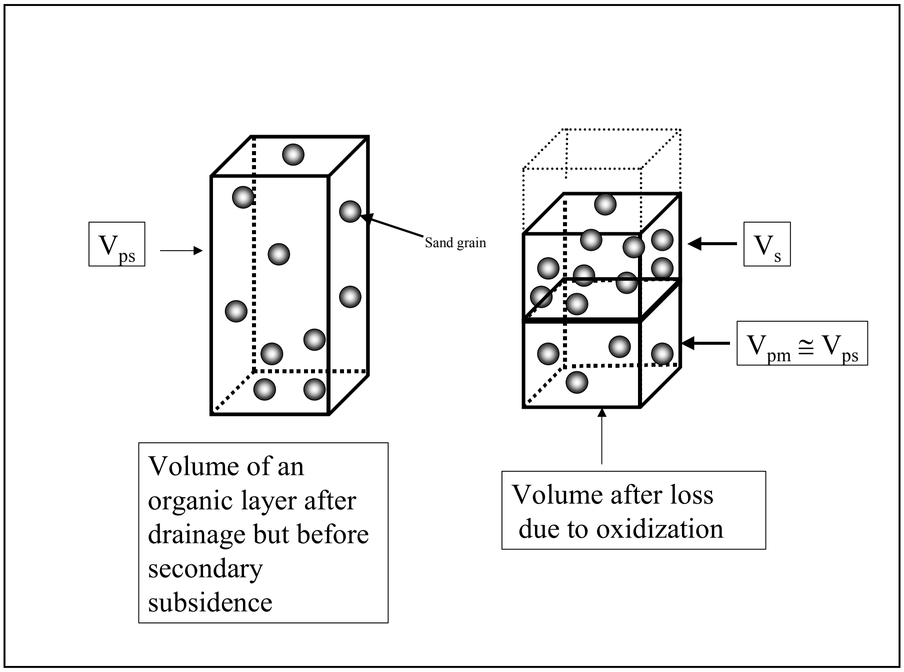

Fig. 3.4. Illustration of how secondary subsidence due to oxidization reduces volume while also increasing the mass in the surface layers by concentrating the sand. V_{ps} is the volume of soil after primary subsidence but before secondary subsidence. V_{pm} is the volume of parent material that has not undergone secondary subsidence and is approximately equal to V_{ps}. V_s is the volume of soil that has undergone secondary subsidence. It is assumed that all volumes have a unit cross-sectional area and changes in volume occur in the vertical direction.

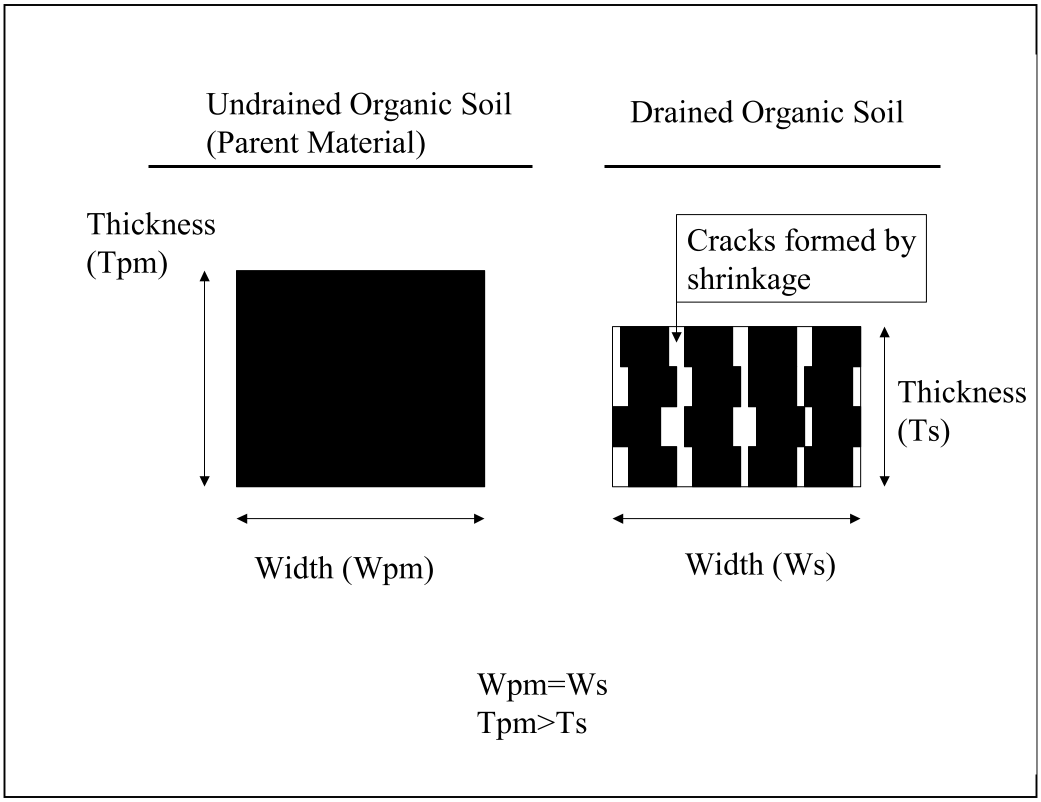

Fig 3.5. When a soil mass shrinks it appears that the shrinkage occurs in all dimensions. However in the horizontal dimension the shrinkage creates voids, and these are part of the soils volume. As a result, the soil's cross-sectional area is assumed to remain constant throughout the weathering process, with changes occurring in the vertical dimension.

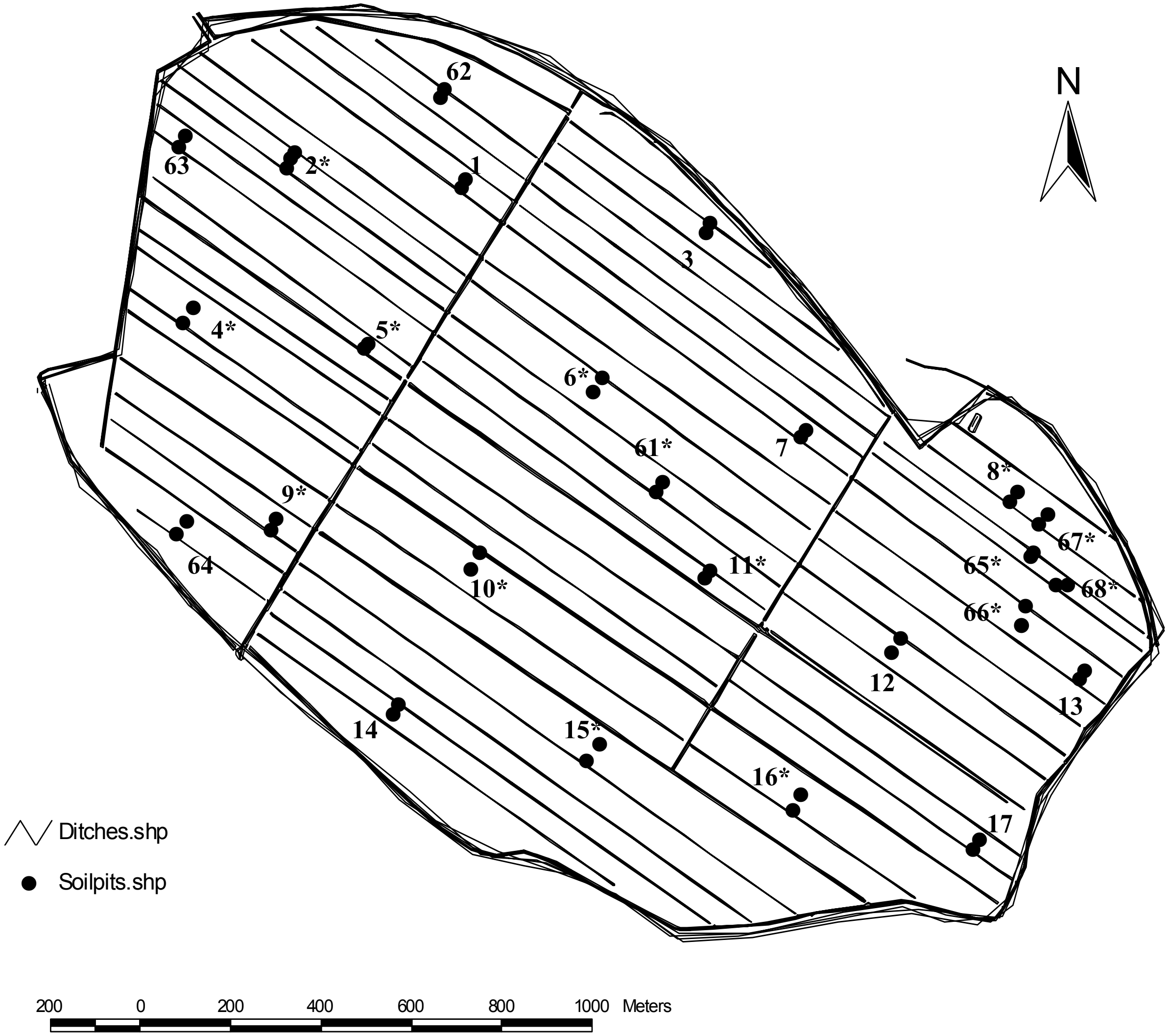

Fig. 3.6. Pit locations at Juniper Bay. *Designates organic soils, all other pits are mineral soils.