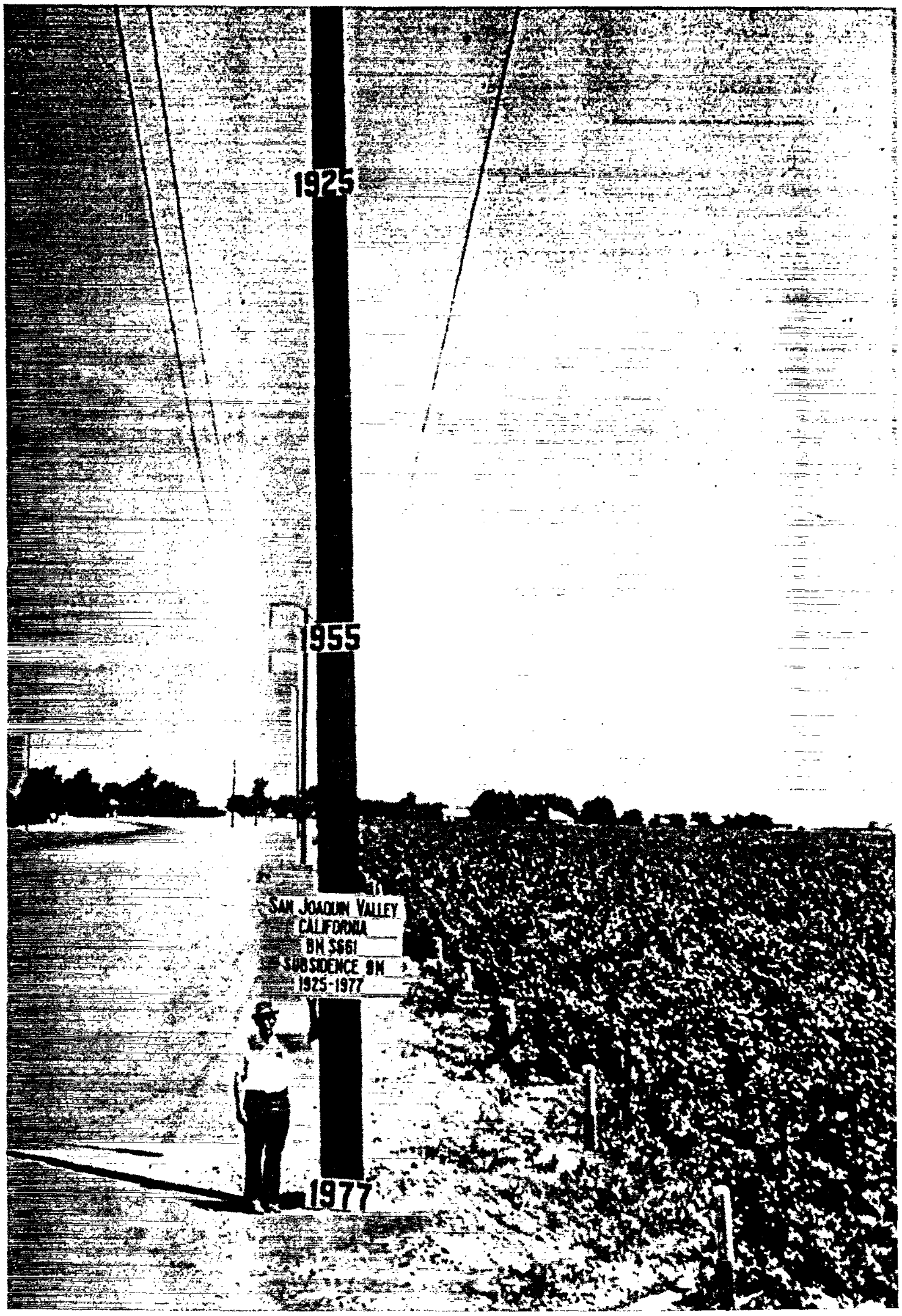
MAN-INDUCED LAND SUBSIDENCE

REVIEWS IN ENGINEERING GEOLOGY
VOLUME VI



Dr. Joseph F. Poland stands at the approximate point of maximum subsidence in the San Joaquin Valley, California. Subsidence of approximately 9.0 m occurred from 1925 to 1977 due to aquifer compaction caused by pumping of ground water. Signs indicate the former elevations of the land surface in 1925 and 1955 respectively. Photo taken December 1976.

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MAN-INDUCED LAND SUBSIDENCE

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Organic soil subsidence

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ABSTRACT

Organic soil subsidence occurs mainly with drainage and development of peat for agriculture. Subsidence occurs either from densification (loss of buoyancy, shrinkage, and compaction) or from actual loss of mass (biological oxidation, burning, hydrolysis and leaching, erosion, and mining). Densification usually occurs soon after drainage is established. Slow, continuous loss of mass is due mainly to biological oxidation. Erosion is minor except in specific sites. Mining losses vary greatly and depend upon direct removal of the materials.

Subsidence rates are determined mainly by type of peat, depth to water table, and temperature. Subsidence losses have been carefully measured in several locations (e.g., the Florida Everglades), and predictions of future subsidence developed in 1950 have proved reliable.

Peat drainage and subsidence have several consequences: loss of plant rooting depth where the substrate is unfavorable (stony, acidic, saline), increased pumping for drainage, instability of roads and other structures, increase in nutrient outflows, colder surface temperature during winter nights, and increase of CO_2 flux to the global atmosphere

The water table for organic soils should be held as high as crop and field conditions allow to reduce subsidence.

Computer models offer methods for refining oxidation rate processes and prediction of subsidence losses where adequate calibration data are available. Remote sensing offers a method of assessing organic soil area and drainage changes. These new technologies should improve our assessment, and guide our management, of organic soil resources.

INTRODUCTION

We present the nature and extent of organic soils, the history, observed rates of sinkage, and causes of organic soil subsidence, the present state of the art in predicting such soil losses, known methods of control, and, finally, a look into the future of organic soil subsidence studies.

Nature and Classification of Organic Soils

Peat and muck soils have unique biological, physical, and chemical properties. Some of the common drainage and agricultural management practices used on mineral soils are not suitable for use on peat soils. Biologically, the organic soils support hosts of micro-organisms that are largely responsible for the formation and alteration of the peat. In an anoxic environment the action of anaerobic micro-organisms break down the parent plant structure and creates peat which accumulates because biomass production is greater than biomass decomposition. Aerobic organisms are largely responsible for decomposition of organic soils under drained conditions.

Peat and muck soils have a dark color, low bulk density, and an absorbent sponge-like texture. They have low albedo for solar radiation and high emissivity for thermal radiation. Compared to mineral soils, they have a high heat capacity when wet, and low heat conductivity. They burn at relatively low temperatures, have a high cation exchange per unit volume, and a high buffer capacity that strongly resists changes in acid reactions. Peat soils tend to be acid but range from pH 3.5 to 8.

Organic soil deposits are classified, under the FAO soil classification system, as Histosol or Gleysols. Histosols must contain at least 12 to 18 percent organic carbon by weight and exceed 30 to 40 cm in depth. Gleysols are mineral soils with gleyed horizons that may be moderately high in organic carbon but contain less than the minimum required for Histosols.

This paper deals only with the Histosols, which are commonly known as peat and muck. Peat and muck develop from the vegetation of bogs, marshes, and swamp forests, or from sphagnum and other mosses, by the action of micro-organisms, under waterlogged conditions. Several taxonomies have been developed and updated in different parts of the world, based on either soil profile properties or botanical composition. One classification defined peat as a soil that has less than 50 percent of mineral matter on a dry weight basis; muck as a soil having 50 to 80 percent of mineral matter; and mineral soils as those having less than 20 percent organic matter. Another usage separates peat and muck based on state of decomposition without regard to organic matter content. Peat soils are usually only partially decomposed and retain a fibrous or granular nature. The mucks are thoroughly decomposed and are finely textured, uniform, amorphous, and black. The principal types of peat, based on botanical origin, are sedimentary, fibrous, woody, and moss. The first three are formed in basins or on poorly drained land. They are known as the low-moor peats. The sphagnum moss types may develop on higher land and are commonly called high-moor peats.

Sedimentary peats are derived primarily from submerged succulent open water plants such a naiads and pond weeds that contain relatively small proportions of cellulose or hemi-cellulose materials. These may be mixed with fecal material from aquatic animals (about one-third on average), with algae and dead micro-organisms, with fallen pollen and leaves from the higher plants together with water or wind-borne mineral sediments. Sedimentary peats are colloidal in particle size, i.e., the clay of organic soils. Drained sedimentary peats seldom yield first-class agricultural soils. Fibrous peats are composed of the remnants of sedges, reeds, and related marsh plants that grow in shallow water of marshes. The fibrous peats contain a reasonably high proportion of cellulose. The water-holding capacity of the fibrous peats is high, and the water transmissibility is satisfactory for drainage and water management for agriculture. They are less acid than the moss peats and have a more desirable texture for tillage than the sedimentary peats. They contain from 2 to 3.5 percent nitrogen. Most of the drained fibrous peats yield good agricultural soils. Woody peats are formed from the climax vegetation in swamp deposits. They develop from the residue of trees and shrubs that occupy the forest floor of the swamp. Woody peat has a lower water-holding capacity than fibrous peat but when drained has a loose granular and blocky structure through which water moves readily. This soil has excellent tilth and usually is rated intermediate between fibrous and sedimentary peat as an agricultural soil.

Moss peats are formed in northerly latitudes where a cool moist climate favors their development. Extensive areas occur in northern Canada and Europe. This peat is formed principally from sphagnum mosses and associated vegetation, which depend upon rainfall, dews, and fogs for moisture and nutrients. The spagnum peats can hold up to 15 or 16 times their weight of water and absorb moisture to the extent that they actually lift the water table above the surrounding country. They build up by layers and sometimes reach a thickness of 30 ft. Generally, they present a dome-shape surface profile. They are extremely acid, pH 3.5 to 4, and are not readily decomposed. Sphagnum peat is a poor medium for the growth of micro-organisms causing decomposition, and the nitrogen content is low. Even when drained, it is a poor soil for the growth of higher plants unless the low pH is raised by the heavy use of lime, and a complete fertilizer is added, which includes the micro-nutrient elements. Sphagnum deposits in Europe and Canada may be used for forest production and as pastures. Some is used in Russia and northern Europe for fuel. Other uses are for the improvement of other soils, such as soil mixes for horticultural use, for packing plants and flowers, as an absorbent litter for stables and poultry houses, and for related uses where its high water-holding capacity is of value. Dawson (1956), Farnham and Finney (1965), Aandahl and others (1974), McCollum and others (1976), and Lucas (1982) review organic soils in further detail.

Extent of Organic Soils

Histosols cover an estimated 21.0 million hectares in the United States (Farnham in Armentano, 1980a; and Lucas, 1982). This includes about 10.9 million hectares in Alaska. Land areas of Histosols are considerably larger than estimates of peat (Moore and Bellamy, 1974). Histosols in the contiguous United States are located mostly in the cool, temperate, humid regions of Maine, Massachusetts, New York, and New Jersey; and in the Great Lakes states of Michigan, Wisconsin, Minnesota, Illinois, and Indiana. The northern glaciated land areas have about 70 percent of the total peat and muck land in the contiguous United States. Deposits also exist in the warm, temperate, humid region within the southeastern coastal plain swamps of Virginia, North Carolina, and Georgia, and along the coastal marsh tidelands of Louisiana and Texas. Other deposits in the Pacific coastal area include

TABLE 1. FOUR ESTIMATES OF THE WORLD'S PEAT LAND RESOURCES (IN 10^6 HA.)

Country	Davis and Lucas (1959)	Moore and Bellamy (1974[1])	Farnham[2]	Lucas (1982)
U.S.S.R.	70.8	71.5	150.0	150.0
Canada	112.5	129.5	112.0	112.0
United States	56.7[3]	7.5	21.0	21.0
Finland	8.1	10.0	9.7	10.0
Sweden	6.1	1.5	7.8	7.0
E./W. Germany	3.0	1.6	5.2	1.6
Great Britain/Ireland	3.2	1.8	5.2	2.6
Poland	2.4	1.5	3.4	1.5
Norway	3.0	3.0	3.0	3.0
Indonesia/Malaysia	1.4	0.7[4]	2.4	18.9[5]
All Others	1.0[6]	1.9[6]	2.2[6]	15.0
Total	268.2	230.5	321.9	342.6

[1]Exploitable peat reserves mainly.

[2]Based on a presentation by R.S. Farnham of the University of Minnesota in Armentano (1980a). See also Heikurainen (1964).

[3]Includes 44.6 x 10^6 ha in Alaska.

[4]Indonesia only.

[5]Includes Sumatra, Kalimatan, Sarawak, Brunei, Malaya, and Papua.

[6]Incomplete global estimates.

the California Delta peats formed where the climate is hot and dry and the marsh and valley deposits in Washington and Oregon. Florida, including the Everglades and related localities, contains about 12 percent of the deposits in the contiguous United States. The Everglades, containing more than 810,000 hectares, is the largest parcel of peat and muck soils in the contiguous United States. The bulk of peat and muck lands, however, are in small scattered pockets of 1 hectare to several hundred hectares. The deposits are valuable for crop production, forestry, natural water treatment, water reservoirs and wildlife refuges, and as a source of organic materials.

Worldwide estimates of the extent of Histosols vary widely. Four estimates of peatland resources are given in Table 1. These estimates are likely incomplete for the less accessible parts of the world. Major uncertainties concern the extent of Histosols in southeast Asia, Canada, Europe, and the U.S.S.R. Farnham, in Armentano (1980a, 1980b), believes that the estimate given by Moore and Bellamy (1974) in Table 1 should be about 40 percent larger, based on larger estimates by Heikurainen (1964) and other sources. Lucas (1982) compiled global estimates of Histosols that are about 49 percent greater than the estimates of Moore and Bellamy (1974).

HISTORY AND RECORDED RATES OF SINKAGE

Netherlands

The oldest records of subsidence appear to be those of the old polders in western Netherlands as related by Schothorst (1977). The low-moor peat soils in these old polders were reclaimed in a period between the 9th and 13th centuries. Initially, the elevation of these peat soils was reportedly equal to or somewhat above sea level. At low tides, excess water could then be discharged by means of sluices into the sea or into rivers. This system of gravitational discharge was possible until the beginning of the 16th century when the surface had subsided to such an extent that excess water had to be discharged artificially by means of windmills. Although throughout the centuries only shallow seasonal drainage was applied, the soil surface nevertheless subsided to about 1 to 2 m below sea level over a period of 8 to 10 centuries. After steam pumping stations began controlling water levels all year long, about 1870, the process of subsidence was accelerated. During the period 1877 to 1965, the polder water level was lowered by 0.5 m. During the same period, the surface subsided an equal amount. The rate of subsidence was 6 mm per year in spite of shallow drainage, which was only 0.1 to 0.2 m below the surface.

Specific records kept of the polder Zegvelderbroek, situated west of Utrecht, show that before drainage in winter was made possible by steam pumps, the total subsidence in the past had amounted to at least 1.5 m—assuming that the initial elevation was equal to or somewhat above sea level. According to historical sources, the polder was reclaimed around 1,000 A.D. Thus, subsidence during the subsequent 9 centuries amounted to approximately 1.7 mm per year. After water control in winter was introduced, however, the subsidence accelerated from 1.7 to 6 mm per year. More detailed data obtained from an experimental field laid out in 1952 for water control in the subject polder showed that a 0.4 m drawdown in the ditch water level over a period of 20 years resulted in a total surface subsidence of 23 cm. In the first 2 years, the subsidence proceeded very rapidly constituting 44 percent of the total for the 20-year period. Subsequently the subsidence rate decreased to a constant 7 mm per year, which is approximately equal to the subsidence rate of the entire polder.

England

The history of drainage, which began in 1652, for the low-moor peats of the English Fens, is largely a story of troubles caused by lowering of the land surface. The story of the Fenlands has been marked by alternate cycles of improved drainage with increased subsidence and consequent higher water tables. First, there was gravity drainage. This was followed by pumpage using windmills, then steam engines, and finally diesel engines. All of these methods greatly increased the rate of water removal but failed to provide a satisfactory solution to the problem of drainage. Frustratingly, the more the water table was lowered by more effective drainage, the more rapidly the peat surface continued to sink; thus, the achievements of one generation became the problems of the next (Darby, 1956). Measurements at the renowned Holme Post, which was solidly imbedded into the underlying clay at Holme Fen about 1848, provides one of the oldest authenticated records of subsidence in existence. This Post shows the lowering of the ground level around the post of 3.14 m in the 84-year period up to 1932 (Fowler, 1933). Thompson (1957) reports that the declining surface elevations continued long after the Fens had become well drained. This subsidence persisted to the date of his last examination in 1957 at a rate variously estimated from a fraction of cm to more than 2.5 cm per year. These historical observations and records of subsidence at Holme Fen are being continued (Hutchinson, 1980). Before drainage began in the 17th century, it is estimated that the peat lands stood 1.5 to 2.1 m above the silt areas. Now the peat is about 2.05 m lower than these areas. Thompson concluded that the continuance of peat subsidence will in time result in the complete elimination of all peat deposits in the region. During a visit to the Fens in 1969, the senior author observed that the peat which had been under continuous drainage had subsided to the point where special plows were needed to incorporate the underlying material in order to provide sufficient depth for cultivation of sugar beets.

Russia and Norway

Skoropanov (1961, 1962) gives an account of peat subsidence in Belorussia at the Minsk Bog Experiment Station. These soils were developed as sedge, sedge cane, and wood cane peat and are classed as low-moor peats with a pH of 5.6. Minsk, U.S.S.R., is near Latitude 54° N. Frost-free days for peat bog soils at Minsk average 123 days. In 1961 thickness of the Minsk peat deposit did not exceed 1.0 m, whereas it was 2.0 m at the beginning of the cultivation in 1914. Research under Belorussian conditions showed that oxidation accounted for 14 percent of the decrement on two plots which had been cultivated for 46 years. Skoropanov contends that oxidation should not be considered as destruction of soil but instead represents the process of soil formation. On the other hand, according to Ivitskii (1962), deep depression of the water table intensifies decomposition of the organic matter by mineralization and that although this process is an integral aspect of soil fertility excessive drainage is undesirable. He recommends that the drainage norm for intertilled crops and grains below bog soils be at least 60 cm but not over 175 cm for the pre-sowing period. During the growing season, he recommends an optimum norm of 120 cm to 130 cm with maximum depth not exceeding 220 cm to 260 cm.

In Norway the principal problem entailed in peatland conservation has been soil destruction brought about by the irrational digging of peat for fuel (Løddesoøl, 1947). Subsidence also occurs, however, under agricultural drainage in Norway. Løddesøl, former director of the Norwegian Bog Association, Oslo, Norway, reported that a loss of 1.5 m in 65 years occurred for cultivated bog soils at Stend Agricultural School at Hordaland County. From these and other observations on 33 parishes, the average loss of about 20 mm per year was shown to occur (Løddesøl, 1949).

U.S.A.

In the organic soils of the Sacramento-San Joaquin Delta of California, the average rate of subsidence has been approximately 8 cm a year with no indication that this rate is decreasing (Weir, 1950). These soils are tule reed peats which have subsided from 1.8 m to 2.4 m with drainage between 1922 and 1950. At the latter date, most of the area was between 3.0 and 3.6 m below sea level and protected by dikes. In Michigan, losses in surface elevation on organic soils as great as 21.5 cm over a 5-year period have been measured, with an average 5-year loss of 9 cm from 13 sites (Davis and Engberg, 1955; Davis and Lucas, 1959). Near Hennepin County, Minn., the total settling of a newly drained peat bog varied from 30 to 60 cm over a 6-year period, with the variation being approximately proportional to water-table depths (Roe, 1936).

In the Everglades of Florida (Stephens and Speir, 1969;

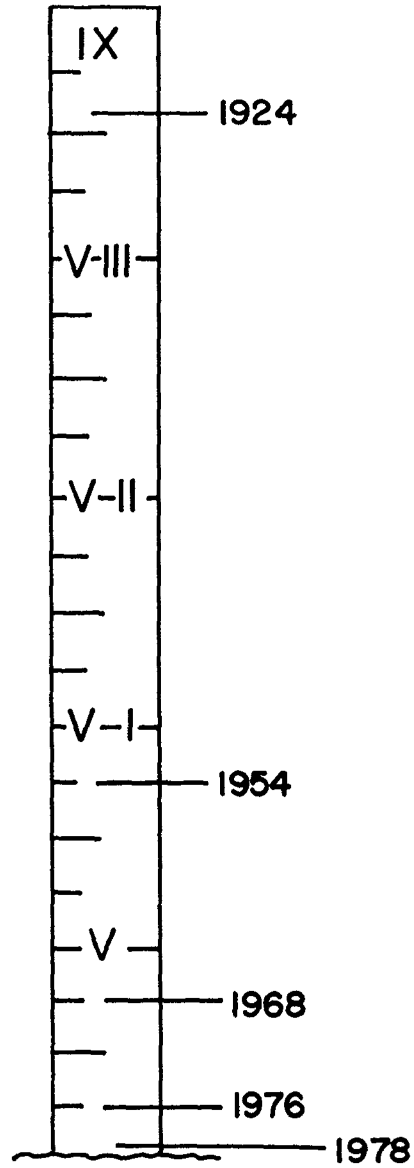

Figure 1. This concrete monument sketch shows a subsidence loss of 1.8 m, occurring between 1924 and 1978 at the Everglades Experiment Station, Belle Glade, Florida. (After Shih and others, Belle Glade, AREC Research rept. EV-1979-1, Mimeo.)

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Figure 2. The subsidence of soil around this house built on piling about 1924 at the Everglades Experiment Station is shown in this recent photograph.

Stephens, 1969), the arable organic soils have an average subsidence rate, after initial settlement, of 2.54 cm per year. This rate is continuing (Shih and others, 1979a). Concrete monuments with their tops originally flush with the ground surface and set directly on the solid underlying rock some 57 years ago now protrude approximately 1.8 m above ground and furnish visual evidence of soil loss. Figure 1 shows losses that have occurred between 1924 and 1978. At Belle Glade and other Everglades towns in Florida, where homes are built on pilings, a new doorstep to the entrance may be needed about every 10 years as the ground subsides (Figure 2). In Indiana and adjacent states, experiments at Purdue University have shown that organic soils subside at about half the rate of those for Florida (Jongedyk and others, 1953).

Global Summary

Worldwide, subsidence rates have been found to vary from less than 1 to more than 8 cm per year. Table 2 shows data from a survey by L. H. Allen, Jr., University of Florida, and J. M. Duxbury, Cornell University. It was compiled for a workshop report on the role of organic soils in the world carbon cycle, (Armentano, 1980a), relating measured rates of subsidence of organic soils for specific sites in different areas.

CAUSES OF ORGANIC SOIL SUBSIDENCE

Disregarding the mining of organic soil for use as a fuel or for agricultural and industrial purposes, organic soil subsidence

TABLE 2. MEASURED RATES OF SUBSIDENCE OF ORGANIC SOILS FOR SPECIFIC SITES IN DIFFERENT AREAS[1]

Location of Site	Annual Subsidence Rate ($cm\ yr^{-1}$)	Cumulative Subsidence (cm)	Time Period (yr)	Average Depth to Water Table (cm)
California Delta (2 sites)	2.5 - 8.2	152 - 244	26	
Louisiana (estimated)	1.0 - 5.0			
Michigan	1.2 - 2.5	7.6 - 15	5	
New York	2.5	150	60	90
Indiana	1.2 - 2.5	7.6 - 15	6	
Florida Everglades (2 sites	2.7 2.7 - 4.2	147 19 - 29	54 7	90 60
Netherlands (2 sites)	0.7 1.0 - 1.7	70 6 - 10	100 6	10 - 20 50
Ireland	1.8			90
Norway	2.5	152	65	
England	0.5 - 5.0	325 (by 1932) 348 (by 1951)	84 103	
Israel	10			
U.S.S.R. (Minsk bog)	2.1	100	47	

[1]Data from survey by L.H. Allen and J.M. Duxbury. Prepared for Armentano (1980a, 1980b).

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has occurred mainly because of drainage and the development of peat deposits for growing food and fiber crops. Thus, we will focus on subsidence processes resulting from agricultural drainage. Under natural conditions of peat formation, water acts as the preservation agent for peat by excluding oxygen.

Causality Classes

Under drainage, six causes of organic soil subsidence are: 1) shrinkage due to desiccation; 2) consolidation, or loss by the bouyant force of groundwater, or loading, or both; 3) compaction, normally with tillage; 4) wind and water erosion; 5) burning; and 6) biochemical oxidation. The first three causes, drying, consolidation, and compaction, increase soil density only and do not cause a loss of soil mass. Such densification is largely a nonrecurring phenomenon. Wind and water erosion or burning may occur occasionally in certain bog deposits and cause significant soil loss. However, these types of losses can usually be controlled. Biochemical oxidation, on the other hand, is a long-term process and continues as long as temperature, pH, and aeration are conducive to microbial oxidation of the organic matter. Thus, the major causes of subsidence can be divided into two main categories: a) physical, which increases soil density and reduces volume only; and b) biochemical, which causes a loss in soil substance and can eventually lead to the loss of the bog deposit (Stephens and Stewart, 1976).

Laboratory Studies

The biochemical aspect of peat oxidation was demonstrated by laboratory studies at Rutgers University as early as 1930 (Waksman and Stevens, 1930; Waksman and Purvis, 1932). Peat types, such as low-moor, high-moor, forest, and sedimentary differ in their chemical composition, in the nature of the microbial flora inhabiting them, and in the rate of attack by micro-organisms. Thus, peats vary considerably in the rate of decomposition depending on different environmental conditions and management. Waksman found for samples of Florida low-moor peat (those with pH from neutral to basic) that about 15 percent of the dry total weight was decomposed at 28° C in 18 months, most of which could be accounted for as CO_2 gas evolved. The optimum moisture content for decomposition was 50 to 80 percent of the total moist peat. Above and below this moisture range, the rate rapidly diminished. Wet and dry cycles greatly stimulated peat decomposition as compared with constant moisture. Broadbent (1960) also observed this effect with California organic soils. In related studies, bacteria were found to be most numerous in drained low-moor peats and less numerous in extremely acid high-moor peats. However, when the acid peats were limed, manured, and put under cultivation, the microbial population increased to about that of the low-moor peats under similar drainage; decomposition rates also increased to that of the low-moor peats. Cold climate retards the activity of micro-organisms. Waksman found that organisms causing decomposition were perceptibly active only when soil temperatures remained above 5° C. Jenny (1930) noted that soil microbial activity generally doubled for each 10-degree increase in temperature. Thus, soil temperature is a factor in determining subsidence rates.

Laboratory studies of the role of micro-organisms in the subsiding of Histosols were made at the University of Florida Agricultural Research and Education Center at Belle Glade by Tate (1976, 1979a, 1979b, 1980a, 1980b), Terry (1980), Terry and Tate (1980), and Duxbury and Tate (1981). Tate traced the microbial reaction sequence involved in peat soil subsidence and in the production of nitrates. He points out that the process usually produces more nitrates than growing plants can use and that the excess is probably volatilized by denitrification, or is removed in drainage water. He suggests that raising the water table will decrease the rate of soil subsidence; hence, decrease the amount of inorganic nitrogen formed, as well as inhibit nitrification. Accordingly, preservation of the organic soils should also help in preserving the quality of surrounding lakes and streams.

Field Studies

Investigations of organic soil subsidence in the Netherlands (Schothorst, 1977), show that compression losses can be reversible or irreversible. In the Dutch polders, a high rate of surface subsidence in summer is largely caused by elastic compression of the peat below groundwater level due to high evaporation rates, which reduces the buoyancy effect. In the winter as the water table rises and the buoyancy effect is recovered, the soil subsidence also recovers almost 100 percent. Thus, in temperate climates where there is a marked difference in water-table levels between winter and summer, it is important that measurements be made at the same season each year to obtain true soil losses. Seasonable subsidence measurements for a 6-year study in three Netherlands polders, with ditch water-level depths that average approximately 65 cm, showed an average annual sinkage rate of 0.53 cm. Schothorst computed the components of loss to be as follows: compression 28 percent (subject to elastic rebound and recovery); irreversible shrinkage 20 percent; and oxidation 52 percent. He found that deeper drainage increased subsidence rates and that higher irreversible shrinkage and oxidation goes with higher levels of organic matter. In the future he expects compression and irreversible shrinkage to gradually decrease, but oxidation to continue at a more or less constant rate until a new, lowered ditch water-level will be necessary.

Typical subsidence rates and patterns for drained organic soils in sub-tropical climates are illustrated by the subsidence line studies in the Florida Everglades south of Lake Okeechobee. The first profile elevations along subsidence lines were surveyed in 1913. In the early 1930's lines were added at the Everglades Experiment Station where land-use and treatment could be controlled (Clayton, 1936, 1938; Allison, 1956; and Neller, 1944). Altogether, 15 lines were established. About 11 are still being surveyed (Shih and others, 1979a). Those abandoned have been negated by construction or have subsided until the organic cover has disappeared and the underlying mineral soil exposed. The original subsidence lines were usually 1 mile long. Elevations were established on permanent bench marks set in bedrock near the point of origin. All elevations were converted to mean-sea-level data and the elevation loss determined by resurveying the lines about every 5 years. Ground elevations were measured every 25 ft along the line, and then averaged to obtain mean elevation of the soil.

Plotted surface elevations vs time show very fast sinkage occurred following initial drainage because of shrinkage and loss of the buoyant force of water. Then, the first tillage caused additional subsidence by compaction. After 5 years of cultivation, the density of the top 45 cm increased to about double that of the brown fibrous peat underneath. The top layer was changed into a black, mucky, amorphous mass with a marked decrease in hydraulic conductivity. As drainage continued, the subsidence rate leveled off to a more or less steady rate, dependent on water-table depth. After the initial rapid shrinkage, due to desiccation or tillage or both, the slow, steady subsidence was largely due to oxidation, which in turn was related to the amount of oxygen in the drained zone.

A graph of the characteristic sequence of observed subsidence in the organic soils is shown for three profile lines (A, B, C, Figure 3). Line A, normal to the North New River Canal just below the old South Bay Lock near the 1-mile post is a peaty muck soil that had gravity drainage before pumps were installed

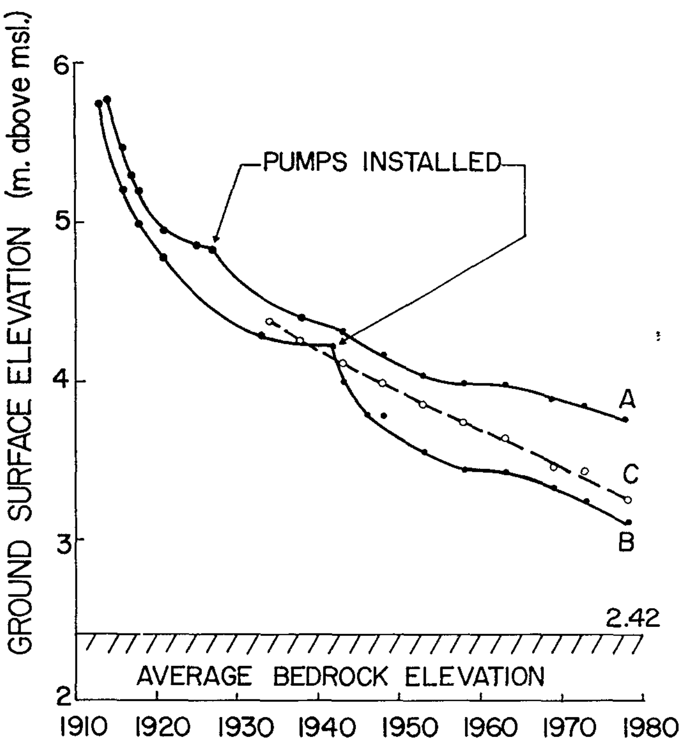

Figure 3. Sequence of observed subsidence of organic soils in the Florida Everglades after initial drainage, circa 1912.

in 1927. Sinkage was rapid during the first 5 years, beginning in 1914. As the ground level fell, gravity drainage was less effective and the subsidence rate decreased. In 1927 the subsidence rate again increased because of pumped drainage and initial tillage. Since 1926 the land generally has been planted to sugar cane and truck crops, and since 1938 the subsidence rate has rather consistently held at 1.60 cm per year. Line B, located 85 m north of the Bolles Canal, a major drain at Okeelanta, is also on peaty muck soil; it had gravity drainage until 1942 when pumps were installed. Historically, this line has had better gravity drainage than Line A. Truck crops were planted sporadically prior to 1953 when the entire area was put into pasture and then converted to sugar cane in 1965. Since 1953 the subsidence rate has been 1.75 cm per year, which is not significantly different from that of Line A for the same period.

Both Lines A and B show typical subsidence patterns: high initial subsidence, a decreasing rate as the ground sank and drainage was impaired, and the consequent increase in the subsidence rates after pump drainage. Line C, located on Everglades peat at the Everglades Experiment Station near Belle Glade, Florida, represents land that has already had its initial rapid subsidence after drainage. It has been continously planted to truck crops since 1934 and probably represents the average subsidence rate (2.44 cm per year) for peat soils planted to truck crops. The subsidence rate of Lines A and B is about two-thirds of that for C. This difference is due to the higher mineral content of the peaty muck soils, or to better pump drainage at the Everglades Station, or both.

It has been observed that grazed sod fields sink slower than adjacent tilled fields under the same drainage. At the Everglades Experiment Station, the annual rate of sinkage in 1950 for the prior three decades was 2.13 cm per year for St. Augustine grass pasture, and 2.67 cm per year for land in truck crops. However, when the entire soil profiles were examined for bulk density and when the higher pastureland elevation was corrected for lower soil density, the difference of loss in soil material between pasture and crop land was not significantly different (Stephens, Craig, and Allison, 1952). A recent analysis by Shih and others (1979b) shows that these trends still hold.

Wind and water erosion have been implicated in causing significant organic soil losses in unprotected fields in Quebec, Parent and others (1982).

PREDICTING SUBSIDENCE RATES

A reliable estimate of the resultant subsidence rate is usually the most important need in determining the economic feasibility of reclaiming organic soils. As previously stated, densification of these soils (caused by drying, consolidation, and compaction) is largely a nonrecurring event and does not cause loss of soil mass. It occurs soon after draining or loading and may be estimated by conventional soil physical formulas, compaction tests, or even short-term observations. Oxidation, on the other hand, is a long-term process that continues as long as temperature, pH, and aeration are conducive to biological oxidation of the soil matter, which can eventually cause the loss of the bog deposit.

Acid peats with a low pH are neither conducive to the growth of micro-organisms that cause a breakdown in oxidation of organic soils nor to the growth of higher plant life common to most agricultural production. A few specialized crops such as cranberries and blueberries do well on acid peats, but these are relatively unimportant in the total agricultural economy. As previously cited, Waksman observed that when acid peats were treated with lime, manured, and put under cultivation the micro-population increased to about the same as that for low-moor peats under similar drainage. Thus, the two principal variables with which we are concerned in determining the rate of subsidence for agricultural soils are a) depth of drainage, and b) soil temperature.

Effect of Depth of Drainage

The relationship between depth of drainage and rate of subsidence has been well established at specific sites where the soil properties are known. The use of controlled water-table plots, where results are available for a period of years sufficient to provide statistically significant data, has proven to give the best guide for computing subsidence rates at representative locations. In all cases, it has been found that the lower the water table the greater the subsidence rate.

At the University of Florida, Everglades Agricultural Experiment Station in 1934, a field of Everglades peat was divided into eight blocks, each 30.5 × 73.4 m (100 by 240 ft) and provided with a system of ditches, underdrains, and check dams so that the water table could be held at any depth desired (Allison and Clayton, 1934; Stephens and Johnson, 1951). Water levels ranging from 30.5 to 91.4 cm (12 to 36 in) between blocks were established in 1936 and held at the same depths until 1943. Surface levels were surveyed and soil samples were taken annually from each block to determine elevation losses and any compaction changes. The rate of subsidence was found to be dependent upon the depth to the water table—the higher the water table the lower the soil loss. Density and mineral content determination showed that all soil losses took place above the water table. By collecting the soil gasses, Neller (1944) found that the production of carbon dioxide (CO_2), end-product of oxidation, was directly related to the amount of soil loss.

At the Purdue University Muck Crop Experiment Station near Walkerton, Indiana, on controlled plots similar to those at the Everglades Experiment Station, the rates of subsidence were found to be about half those for Florida (Jongedyk, 1950, 1953). This difference can be explained when water-table treatments are considered. Prescribed water tables were held year round in the Florida experiments, while in the Indiana experiments the lowered water tables were held only during the crop year from May to September. Furthermore, during the winter season, the Indiana plots were exposed to freezing temperatures. The significant results from the Florida and Indiana water-table studies on subsidence rates are summarized in Figure 4.

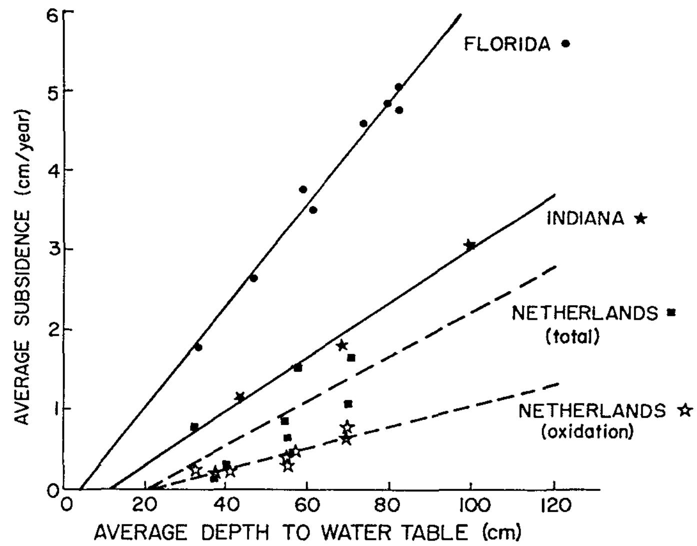

Figure 4. Comparative subsidence rates of organic soils in Indiana and the Florida Everglades versus water-table depth. Organic soil data for western Netherlands superimposed from Schothorst, 1977. The two lines shown for the Netherlands show total subsidence and subsidence attributable to biological oxidation. The linear regression equations are (a) Florida: $Y = 0.0643X - 0.259$; (b) Indiana: $Y = 0.0344X - 0.429$; (c) Netherlands (total subsidence): $Y = 0.0281X - 0.581$; (d) Netherlands (oxidative subsidence): $Y = 0.0134X - 0.291$; where Y is the predicted subsidence in cm per year, and X is the average depth to water table in cm.

The annual subsidence rate of low-moor peat soils for the Zegvelderbroek water-table experimental plot in the western Netherlands, (Schothorst, 1977), is also shown on Figure 4. This soil is similar to the Florida and Indiana peats in organic matter content. The Netherlands rates differ from those in Florida and Indiana; however, the rates are not strictly comparable since the Florida and Indiana losses were primarily from oxidation, whereas the Netherlands rates included initially higher sinkage rates for the first three years of drainage in addition to oxidation losses. Schothorst noted that subsidence occurred somewhat more rapidly during the initial years of the six-year study.

Coefficients for linear regression of annual subsidence rates vs depth to water table are given in the caption of Figure 4.

Effect of Soil Temperature

Although known for years that subsidence of organic soils was faster in warmer regions than in cooler climates, as witnessed by the Florida vs Indiana water-table studies, it has been only in the past decade that much progress has been made in relating soil temperatures to subsidence.

Laboratory studies, (Knipling and others, 1970; Volk, 1973), determined the rate of CO_2 evolved from peats as a function of soil temperature. Both studies showed that CO_2 evolution increased with water-table depth and with temperature. Knipling found that from 10° to 20°C the CO_2 rate of change was smaller than that from 20° to 60° C, but that generally CO_2 evolution rates doubled for each subsequent 10° increase. Volk found that CO_2 losses were directly proportional to water-table depth and to temperature, and were also a function of organic content and bulk density. He also found that each 10° C increase about doubled the CO_2 evolution, within normal soil temperature ranges. Further, for a given water-table depth and temperature, he found that the amount of CO_2 involved increased as the percentage of organic matter increased. Volk ascribed the reduction in biochemical activity for the higher density mucks, as contrasted to peats, to the higher mineral content of the soil fraction that formed a clay-organic complex less accessible to the micropopulation.

In studying the effects of climate on soil subsidence, Stephens and Stewart (1976) compared the rates of CO_2 released, as determined by the laboratory studies of Knipling and Volk, to the measured rates of soil subsidence at the Everglades Experiment Station water-table plots. By converting subsidence rates for peat soil solely due to CO_2 evolution, they found that for these soils (bulk density 0.18 g/cm^3) a CO_2 flux density of about 1.0×10^{-8} $g/cm^2/sec$ would be required to produce an elevation loss of 1 cm annually, assuming that the subsidence rates were due solely to oxidation of carbon to CO_2. The measured annual subsidence rate for the 60 cm depth water-table plot, where the annual soil temperature was 25° C, was 3.76 cm per year (Figure 4). The laboratory CO_2 evolved at the 60 cm depth at 25° C was 1.9×10^{-8} $g/cm^2/sec$, which computes to a subsidence loss of 2.00 cm per year for the lab studies, or which accounts for approximately 53 percent of the measured loss in elevation for the water-table plots. However, the CO_2 evolution accounts only for the loss due to microbial respiration. It does not account for the loss of material hydrolized by microbial action, which is removed by leaching under field conditions, or for compression or compaction. For the water-table plots, Neller (1944) judged that only a small part of the subsidence could be attributed to compaction since he found no increase in bulk density over a period of six years. However, his density studies were too few to be conclusive. We estimate that the increase in density during the years for which Neller reported (1935–41) did not exceed 10 to 15 percent. Thus, the loss of hydrolized material by microbial action, which is removed by leaching, could be as much as 25 to 30 percent according to the experimental data cited. Whatever the exact contribution of the leachates from hydrolized organic material to biochemical subsidence, it is the same group of organisms that evolves CO_2 gas, and thus may react in the same manner to a change in soil temperature.

We recently attempted to estimate carbon losses from the Everglades Agricultural Area in the drainage water pumped into the conservation area based on data of Lutz (1977) and/or in the drainage water pumped into Lake Okeechobee based on data of Dickson and others (1978). Davis (1981) data showed that the C/N ratio of drainage water was about 7. A typical areal export rate of N was 36 kg/ha per year (Dickson and others, 1978). Multiplied by 7, this would yield an areal export rate of C of about 250 kg/yr. Assuming a 2.5 cm per year subsidence rate, and a C density of 0.1 g/cm^3, we would expect a loss of about 25,000 kg C per hectare. Therefore, the water transported C leaving the Everglades Agricultural Area appears to be only of the order of 1 percent of the total amount of C lost as a result of subsidence. However, it is possible that losses of both gaseous C and N could occur between the point where leachates leave the fields and the point where they are pumped out of the Everglades Agricultural Area. Nevertheless, these data suggest that losses of hydrolized materials are small compared to decomposition to CO_2 and other gases.

Linking Drainage and Soil Temperature

In developing a mathematical model linking drainage depth and soil temperature that could be used to estimate subsidence of low-moor peats in different climates, Stephens and Stewart (1976) applied the Arrhenius law to both water-table and laboratory findings. (Arrhenius showed that the logarithm of the velocity coefficient, k, of a chemical reaction is linearly related to the reciprocal of the absolute temperature, T.)

With the assistance of Victor Chew, biometrician, USDA, ARS, Gainesville, Florida, they developed the "Stephens-Stewart-Chew" basic subsidence equation, which follows:

$$S_T = (a + bD)\, e^{k\,(T-T_o)}, \tag{1}$$

where

S_T = biochemical subsidence rate at temperature, T.
D = depth of watertable
e = base of the natural logarithm
k = reaction rate constant
T_o = threshold soil temperature where biochemical action becomes perceptible
a and b are constants

Using the empiricism that S_T multiplies to $Q_{10} \cdot S_{(T+10)}$ where Q_{10} is the change in reaction rate for each 10° C rise in temperature, then

$$S_{(T+10)} = Q_{10} \cdot S_T = (a+bD)\, e^{k.\,[(T+10)-T_o]} \tag{2}$$

Dividing eq. (2) by eq. (1):

$$\frac{S_{(T+10)}}{S_T} = Q_{10} = e^{10k} \tag{3}$$

By rewriting (2) to express k in terms of Q_{10},

$$k = 1/10 \ln Q_{10}, \tag{4}$$

and substituting (4) into (1),

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$$S_T = (a + bD)\ Q_{10}^{(T-T_o)/10} \quad (5)$$

From laboratory studies, the value of Q_{10} was assumed to be 2.0 and the value of T_o to be 5° C. The relation found between drainage depth, soil temperature, and annual subsidence rates at the Everglades Experiment Station water-table plots was chosen to find the value of constants a and b where measured annual soil temperature was 25° C. Thus, from Figure 4, when D = 40 cm, S = 2.29 cm/yr, and D = 80 cm, S = 5.00 cm/yr. Substituting these values into (5) and solving the simultaneous equation to evaluate a and b, we find that a = –0.1035 and b = 0.0169. Then from (5)

$$S_x = (-0.1035 + 0.0169\ D)\ (2)^{(T_x - 5)/10} \quad (6)$$

Stephens and Stewart recommended that equation (6) be used to estimate the biochemical subsidence rate for low-moor organic soils at locations where the annual average soil temperature at the 10-cm depth is T_x.

For example, equation (6) was used as follows to estimate the annual subsidence rate—exclusive of compaction or other bulk density change—at the Lullymore Experimental Station in the Irish Republic for the arable low-moor soils where the average annual soil temperature is 8.5° and the water-table depth is held at 90 cm:

$$\begin{aligned} S_L &= (-0.1035 + 0.0169 \times 90)\ (2)^{(8.5 - 5.0)/10} \\ S_L &= 1.4175 \times 2^{0.35} \\ S_L &= 1.4175 \times 1.27 = 1.80 \text{ cm/yr} \end{aligned} \quad (7)$$

This indicates that if the Everglades Histosols were transposed to Lullymore, the rate of decomposition would be only 32 percent of the rate in south Florida where T = 25°.

If the Everglades soils were in a more tropical climate where the average soil temperature was 30° C, for example, again from (6)

$$\begin{aligned} S_x &= (-0.1035 + 0.0169 \times 90)\ (2)^{(30-5)/10} \\ S_x &= 8.02 \text{ cm/yr} \end{aligned} \quad (8)$$

which is a rate 43 percent greater than the decomposition rate for south Florida.

For convenience in estimating S_x for any selected temperature, T_x, the results from equation (6) were plotted at water-table depths, D, of 30, 60, 90, and 120 cm, which has been reproduced as Figure 5.

Stephens and Stewart cited limitations of the mathematical model due to limited field and lab data, but also pointed out that if future studies indicated the values of Q_{10} and T_o should be different from those assumed, the mathematical procedure for computations would still be valid. Only the constants for a and b would change. For instance, where Q_{10} = 1.5 and T_o = 0° C, then a = – 0.1523, and b = 0.0246.

When using equation (6) or the graph, Figure 5, remember

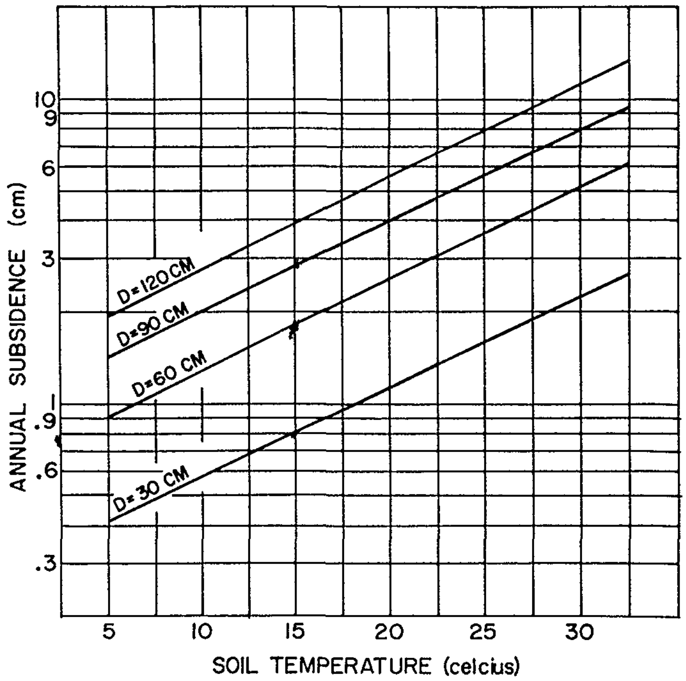

Figure 5. Annual subsidence of organic soils at various water-table depths and soil temperatures.

these values were developed from organic soils with a mineral content of less than 15 percent and a bulk density of approximately 0.22 g/cm³. With muck soils of increased mineral content, and higher bulk density, the expected subsidence rates would be from one-half to three-fourths of those shown by the subject graph, or equation, depending on the increase in mineral content.

CONTROLLING SUBSIDENCE

Presently, organic soils cannot be used for crops that require drainage without paying the cost of subsidence. The rate can be slowed by proper water control and good land management. Crop yield studies indicate a water table of 30 to 60 cm for sod, and one of 60 to 90 cm is desirable for most truck and field crops on peat (Snyder and others, 1978). Thus, even with optimum water-table control for good production, subsidence will continue at an undesirable rate. On seasonally cropped lands, flooding during the idle season could lengthen the life of organic soils. Growing water-tolerant crops such as rice or kenaf could add many years to the life of peatlands. However, several agronomic, economic, and institutional problems have to be solved before many of the water-tolerant crops can be grown commercially.

The value of plowing under litter or cover crops to prolong the life of organic soils is debatable. A study in 1968 was made using radiocarbon age determinations to ascertain the rate of peat formation in the upper Everglades (McDowell and others, 1969). These age determinations indicate that peat formation began during late Hypsithermal time, about 4,400 years ago. About 500 to

1,000 years were required to build up an 8 cm layer of basal, mucky peat composed of a mixture of marl and organic matter. Then about 3,500 to 4,000 years ago, coincident with a rise in sea level or the climatic optimum, or both, plant growths were preserved as fibrous peats with little mineral admixture, and peat soils developed relatively rapidly. By 1914, peat had developed to a depth of about 3.7 m at the sample sites, which represents an average peat development of about 9 cm per century. Age determinations of moss and forest peat in the Netherlands polders show an accumulation rate of 10 cm per century (Van der Molen, 1981). In Scotland, radiocarbon dating and pollen graphs show that basin peats have accumulated at rates of from 8.0 to 9.6 cm per century during the last 2,500 years since the beginning of the wetter Atlantic Climatic Period, while the moss hill peats were accumulating at a much slower rate of 4.8 cm per century (Durno, 1961). Initially, it was concluded that in Florida turning under cover crops would be trivial, since the 9 cm of peat, which required 100 years to develop, would be lost by oxidation in about two years with a drainage depth of 70 cm. On the other hand, some scientists believe that organic soil deposits might recover faster than radioactive dating of natural strata would indicate. They suggested that managed flooding might restore deposits faster, because of no misfortunate losses due to desiccation during natural drought cycles that could lead to intermittent biologic oxidation, or to fire, or other catastrophic losses.

In any event, barring a fortunate and now unforeseen breakthrough in the science of organic soil conservation, subsidence will continue on drained, cropped Histosols. Meanwhile, several steps may be taken to obtain the maximum agricultural use of these soils: 1) provide adequate water control facilities for keeping water tables as high as crop and field requirements will permit; 2) make productive use of drained lands as soon as feasible; and 3) intensify research studies to develop practices to prolong the life of the soils.

A LOOK AT THE FUTURE

New Mathematical, Biochemical, and Agronomic Investigations

Agricultural scientists have started an intensive team effort, including field, laboratory, and mathematical approaches, aimed at better defining the specific causes of biochemical subsidence and gathering better insights into the interrelationship of the causes. In connection with these studies, Browder and Volk (1978) developed a computer systems model that simulates the interaction of climatic and biologic factors on the biochemical oxidation of Histosols following drainage. This model conserves the mass balances of carbon and nitrogen as they are transformed in a series of complex rate processes. Predictions, based in part on estimates of rate process data, gave results reasonably consistent with historical records. Simulations were designed to show the effects of temperature, depth to water table, and organic composition on CO_2 evolution. Simulation results showed that temperature and water-table depth have the greatest effect, which is similar to earlier experimental conclusions. It is hoped that such studies will help researchers develop a better understanding of how the organic soil system works and identify those factors that have the greatest impact on subsidence, so that additional research studies can be concentrated in those areas.

Studies have been initiated to try to determine the biological and enzymatic factors involved in biochemical oxidation of Histosols (Duxbury and Tate, 1981; Tate, 1976, 1979a, 1979b, 1980a, 1980b; Terry, 1980; and Terry and Tate, 1980). So far, these studies have not given successful clues for reducing subsidence of drained organic soils.

Alternative crops that can be grown under flooded or waterlogged conditions offer one possibility of reducing or eliminating subsidence. Morton and Snyder (1976) reviewed the potential of numerous aquatic crops such as watercress, water spinach, swamp fern, vegetable fern (pako), water dropwort or water celery, ottelia, asiatic pickerel weed, bengok, jungle rice, rice, wild rice, Chinese water chestnuts, swamp potato, lotus root, taro, and dasheen. Snyder and others (1977) reviewed the economic potential of incorporating rice into Everglades vegetable production systems. Crops that can be grown in flooded or waterlogged conditions offer the best opportunity of preserving and utilizing the organic soil resource.

If subsidence continues, many of the developed organic soils will have to be returned to a continuously saturated state. Deep organic soils such as in the Sacramento-San Joaquin Delta of California are already below sea level, and the peat will not support unlimited levee loads. Shallow organic soil such as in the Everglades Agricultural Area of southern Florida will eventually leave rock exposed. In either case, either a wetlands agriculture will have to adapt or the areas designated for other nonagricultural use.

Subsidence and the Global Carbon Cycle

One question that has been raised recently is the role of organic soils in the global carbon cycle. Based on measurements of subsidence rates ($\sim$2.54 cm/year), knowledge of soil properties (bulk density $\simeq$ 0.23 g/cm^3; % organic matter $\simeq$ 88%, % C of organic matter $\simeq$ 56%), and knowledge of the area drained ($\sim 3.1 \times 10^5$ ha), we computed the carbon released to the atmosphere annually from the Everglades Agricultural Area of Florida to be about 9×10^{12} g carbon. Since the recent rate of release of carbon from fossil fuels is about 5×10^{15} g, oxidation subsidence in this area is equivalent to about 0.18 percent of that released by fossil fuels. In order to meet the carbon-equivalent of the global annual fossil fuel usage, a 14 m depth equivalent of the Everglades Agricultural Area organic soil would be required. For the Sacramento-San Joaquin Delta, assuming the same soil properties, a subsidence rate of $\sim$7.6 cm per year, and a drained area of $\sim 1 \times 10^5$ ha, a carbon release of about 7.6×10^{12} g annually was

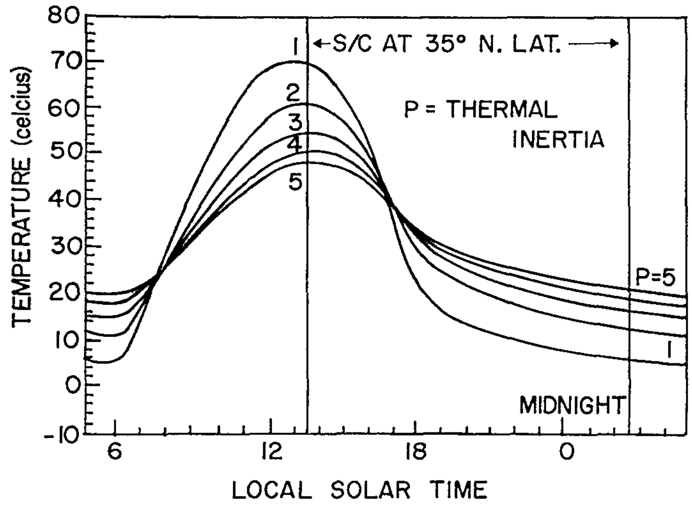

Figure 6. Illustration of diurnal surface temperature variation as a function of thermal inertia (from Heat Capacity Mapping Mission (HCMM) Data Users Handbook for Applications Explorer Mission-A (AEM), Goddard Space Flight Center, NASA, Greenbelt, MD, Dec. 1978, Sec. Rev. Oct. 1980). The unit value of P is 41.86 kJ · m^{-2} · $s^{-½}$ · $°K^{-1}$.

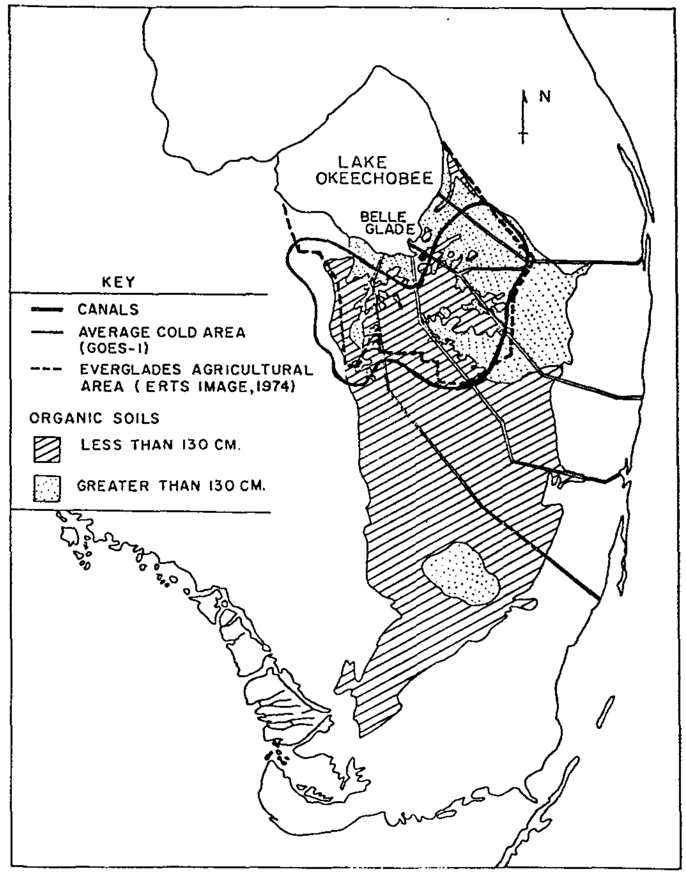

Figure 7. Comparison of Everglades Agricultural Area and Satellite Sensed Cold Area. (Adapted from Chen and others, 1979.)

computed, which is equivalent to about 0.15 percent of the carbon released annually from fossil fuels.

A workshop called "The role of organic soils in the world carbon cycle" estimated that the current annual release of carbon from organic soils falls within the range of 0.03 to 0.37 × 10^{15} g, which is equivalent to 1.3 to 16 percent of the annual increase of carbon in the atmosphere (Armentano, 1980a). If half of the released carbon remains in the atmsophere, then organic soils were estimated to contribute 0.6 to 8.0 percent of the annual rise in CO_2. Uncertainties in the data indicate that the actual release could lie outside this range. Evaluation of organic soil areas, drainage status, and biological oxidation rates are needed on a global scale to reduce the uncertainties.

Remote Sensing Potentials

Remote sensing offers much promise for assessing both the area and water status of organic soils now and changes that may occur in the future. Aerial photographic interpretation has been used for several years to assess muskeg areas in Canada (Korpijaakko and Radforth, 1968). Scientists at the Department of Peat and Forest Soils, Macauley Institute for Soil Research, Aberdeen, Scotland, have made significant advances in peat surveys by application of remote sensing techniques using Landsat satellite imagery and airborne sensor devices. Information can now be obtained on land use, peat and forest resources, crop conditions, water deficit or excess, and several other surface features (Stove and Hulme, 1980). Chen and others (1979, 1982) showed that drained organic soils could be clearly distinguished from undrained organic soils in Florida based on nocturnal surface temperatures from Geostationary Operational Environment Satellite (GOES) data. A combination of global soils map, visual sensors (reflected solar radiation), and thermal sensors (emitted radiation) could be calibrated to delineate more clearly the areas of organic soil on a global basis. The satellite systems are now available to do the job. The data analysis packages are available to discriminate various surface conditions. It only remains for someone, or some group, to apply the technology: first in an experimental phase, to determine how accurately organic soil surfaces can be distinguished from other surfaces, and then in an operational phase, to determine the areas and drainage status of the soils. Already, on a local scale, some remote sensing technology is being developed using reflected solar radiation and microwave energy. In 1980, a unit called Remote Sensing was formed within the Macauley Institute for Soil Research in Scotland to utilize information that can be obtained from satellite imagery and enhanced by radar coverage from the newer U.S. satellites and the European space programs. Newly acquired electronic stereoplotters, digitizers, and computer hardware are expected to greatly upgrade the efficiency of present Macauley Institute equipment for remote sensing research (West and others, 1981).

Not only areas, but also the drainage condition of organic soils could be estimated from remote sensing based on thermal inertia (sometimes called conductive capacity) of the surface. Thermal inertia = $(\lambda C)^{½}$, where λ = thermal conductivity and C

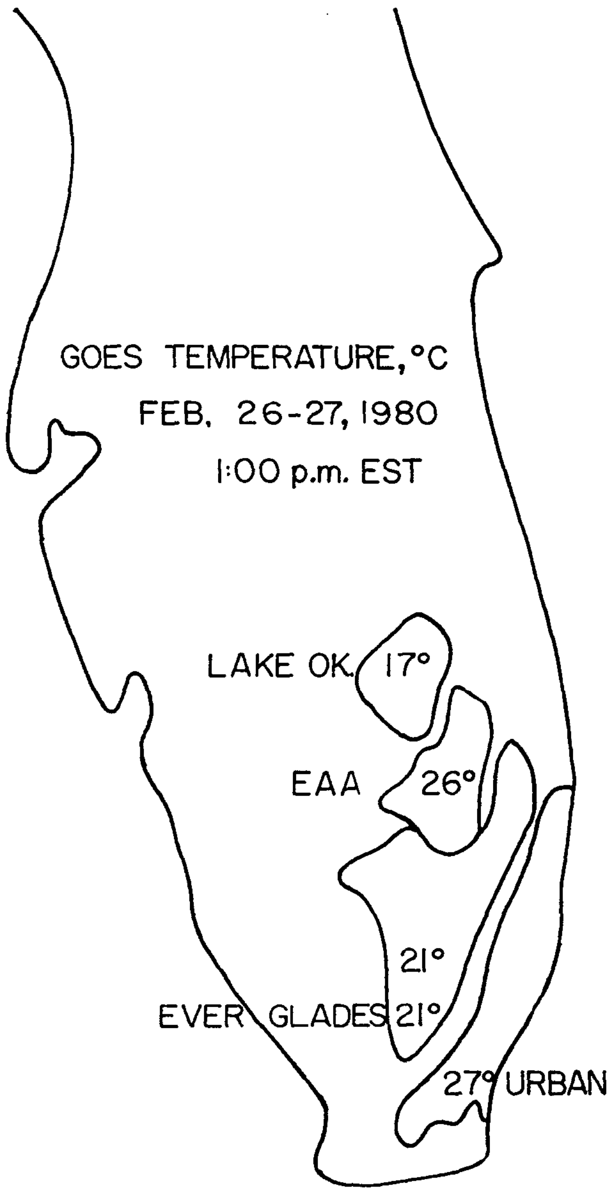

Figure 8. GOES derived surface temperature maps for 1:00 P.M. EST (early afternoon) on February 26, 1980.

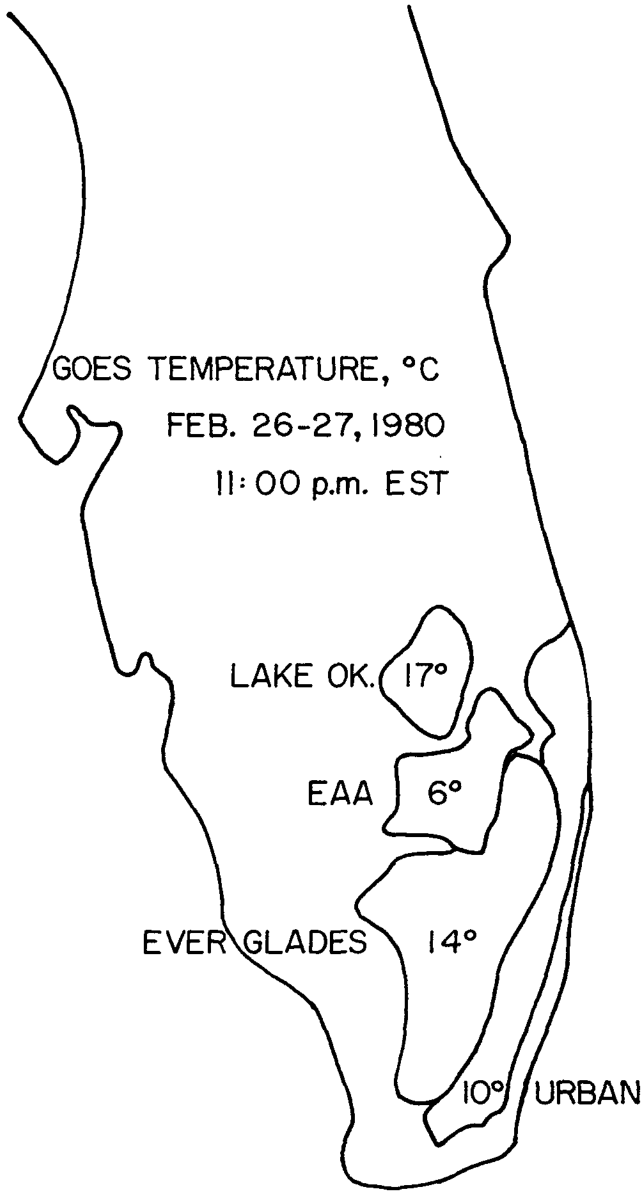

Figure 9. GOES derived surface temperature maps for 11:00 p.m. EST (late evening) on February 26, 1980.

= heat capacity. Thermal sensors can be used in twice-daily polar orbiting overpasses, or from hourly data from the GOES, to detect differences in surface temperature from typical early afternoon maxima to predawn minima. Drained organic soils have a low thermal inertia because of (a) low heat capacity due to low water content, and (b) low thermal conductivity of the remaining organic matter. On the other hand, undrained or flooded organic soils have a different (greater) thermal inertia.

A case in point will be discussed. Figure 6 shows a family of lines of thermal inertia. This figure illustrates that surfaces with low thermal inertia would be expected to have higher early afternoon temperatures and lower predawn temperatures than surfaces with high thermal inertia.

Figure 7 shows the southern end of Florida, with four identifiable areas:

1. Lake Okeechobee
2. Drained Everglades Agricultural Area (EAA)
3. Undrained Everglades with shallow organic soils
4. Southeastern Urbanized or Developed area.

A fifth area of mineral soils in Hendry County, just west of the EAA, was not marked on Figure 7.

The next series of three figures, (Figures 8, 9, and 10) show Geostationary Operational Environmental Satellite derived surface temperature maps for three times on February 26-27, 1980, during clear sky conditions. (The maps are distorted slightly by elongation because it was dawn from a computer printer symbol-

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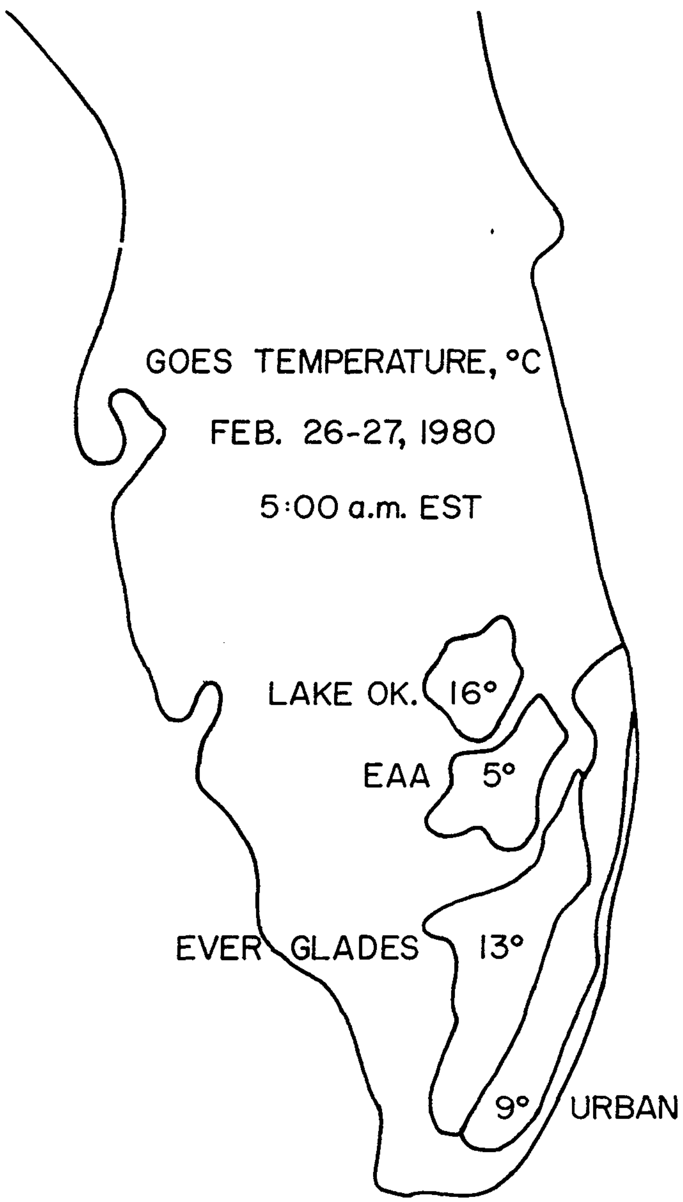

Figure 10. GOES derived surface temperature maps for 5:00 a.m. EST (predawn) on February 27, 1980.

coded map.) The three time periods shown are 1:00 p.m. (early afternoon), 11:00 p.m., and 5:00 a.m. (predawn). The surface temperature information at each time in each of the above identified areas is summarized in Table 3.

During early afternoon on February 26 (1:00 p.m.), the highest temperatures were in the Urban/Developed strip along the Southeast Coast (27° C). The area would be characterized by lower evapotranspiration, but with considerable thermal inertia. The next highest mid-day temperatures were in the Everglades Agricultural Area (26° C). This area is drained and had low

TABLE 3. GOES SURFACE TEMPERATURES IN DEGREES CELCIUS IN SOUTH FLORIDA AT THREE TIMES DURING A DIURNAL CYCLE ON FEBRUARY 26-27, 1980

Time (EST)	Hendry Co.	Lake Okeechobee	EAA	Ever-glades	Urban/ developed
1:00 p.m.	23	17	26	21	27
11:00 p.m.	9	17	6	14	10
5:00 a.m.	8	16	5	13	9
Range[1]	15	1	21	8	18

[1]Difference in surface temperature between 1:00 p.,m. EST February 26 and 5:00 a.m. EST February 27, 1980.

thermal inertia in the surface layers. Over the whole area, evapotranspiration can be moderately high because only a part of the sugarcane is harvested by February 26. The next highest temperatures (for comparison here, but not illustrated) were in Hendry County just west of the EAA (23° C). This is a rural area of mineral soil with higher thermal inertia than the EAA. The Everglades surface temperature was lower at 21° C, and Lake Okeechobee was lowest at 17° C. The EAA has higher thermal inertia because of water at or near the surface. Lake Okeechobee has the highest thermal inertia of all, and, of course, has the ability to mix the waters.

By 11:00 p.m., the surface temperature patterns have changed completely. Lake Okeechobee had the highest temperatures (17° C), whereas the EAA had the lowest (6° C). Of the land surfaces, the Everglades (undrained) had changed the least, dropping from 21° C to 14° C, which indicates that it had a much higher thermal inertia than the drained EAA. The mineral soil surface of Hendry County appeared to have a lower thermal inertia than did the undrained Everglades, but greater than the EAA, actually about midway between. The Urban/Developed area had a large temperature drop that was partly due to high temperatures of nonevaporating surfaces during the day.

There may have been a slight latitudinal gradient of temperatures, but the maps show clearly that there was a wide difference in surface thermal responses of the undrained and the drained organic soils.

Also, this example shows how in the future we may be able to detect and quantify areas of drained and undrained organic soils on other parts of the earth. The technology and capability is just around the corner. Predicting rates of subsidence and contribution to the global carbon cycle will be more difficult, but we anticipate that much better estimates can be obtained in the future.

ACKNOWLEDGMENTS

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