Genesis, classification and human modification of peat and mineral-organic soils, Hula Valley, Israel

M.I. Litaor[1], O. Reichmann[2] and M. Shenker[2]

[1]Tel-Hai College, and MIGAL Laboratory, Upper Galilee, Israel
[2]Department of Soil Science, The Hebrew University of Jerusalem, Israel

_____

SUMMARY

In the last six decades, the pedosphere of the Hula Valley, Israel, has been subjected to major management changes that have led to intense soil alterations. From a thriving East Mediterranean wetland complex characterised by peat and mineral-organic soils, it was converted in the 1950s to intensively cultivated farmland. After four decades of cultivation with numerous agro-technical difficulties and environmental problems, the least fertile soils were re-flooded to form a small lake called Agmon. Construction of Lake Agmon raised the water table in the surrounding soils, creating new hydrogeochemical conditions that changed the pH, redox potential, adsorption-desorption characteristics, rate of organic matter oxidation and soil structure. In this article, we review the history of pedological research in this area, discuss the various soil classification schemes devised at different times before and after drainage, and present a case against an attempt to produce new soil maps because frequent land-use changes and continuous internal soil processes make them rapidly inaccurate. For future land use planning and management, we recommend adapting a probability-based approach that models the values of continuous soil attributes, produces probability maps and quantifies the acceptance of uncertainty.

KEY WORDS: drainage; peatland, pedology; soil survey; wetland

_____

INTRODUCTION

Prior to its drainage in the late 1950s, the Hula Valley was characterised by a mosaic of wetlands, ponds, streams, springs and a shallow lake. Following drainage, the dewatered soils were converted to farmland, but this newly formed soilscape was to be short-lived. The peat soils subsided by an average of two metres from their original elevation because of inadequate agro-management practices. This led to structural degradation, accelerated wind and water erosion, rapid oxidation of organic matter (OM) and occasional soil conflagration (internal combustion) (Shoham & Levin 1968, Shaham *et al*. 1990). After four decades of intensive cultivation, the least fertile areas were re-flooded in 1994, forming a small lake that was named Agmon and causing a pronounced rise of the water table to 1–2 m below the surface, depending on the season. The peat soils have not reached a steady state and their major properties such as OM content, pH, buffering capacity, base saturation, bulk density and other physical and chemical attributes, are still changing.

Studies on the genesis and classification of the Hula Wetland soils began in the early 1930s, before they were drained, and were revisited following the land-use changes. However, most of the soil surveys, classifications and genesis reports were published in Hebrew and are not available in electronic form. Furthermore, in light of the continued changes in land use and land cover, and partial conversion of the valley from farming to ecotourism, it is of interest to summarise the past and current state of pedological knowledge. Hence, the aim of this work is to summarise and synthesise the existing reports and provide some insight into present and possible future directions of pedological investigations in this altered East Mediterranean wetland. We present a summary of the genesis and classification of the soils in the Hula Valley based on past pedological research, as well as new data gathered from a few locations that have undergone intense alterations in the last decade. We cover a period in which substantial management changes took place in the valley and this article may, therefore, reflect alteration trends leading to the present characteristics of the Hula Valley soils.

GEOGRAPHICAL SETTING

The Hula Valley is the northernmost segment of the Jordan-Arava Rift Valley, and lies approximately 70 m above sea level. Its total area is approximately 175 km^2, while the extent of the drained Hula lake

and swamps complex varies from 21 km^2 at the end of summer to 60 km^2 at the height of winter (Dimentman *et al*. 1992) (Figure 1). The climate of the Hula Valley is typically East Mediterranean; i.e. hot, dry summers with an average temperature of 28 ℃ in July and cool, wet winters with an average temperature of 12 ℃ in January. The average precipitation in the study area is 400 mm year^{-1}, and the current monthly evapotranspiration rate varies between 90 mm month^{-1} in winter and 240 mm month^{-1} in summer (Tsipris & Meron 1998).

EARLY SOILS RESEARCH

In the early days of soil studies and surveys in the Hula Valley, Ravikovitch (1936) and Reifenberg & Moshicky (1941) investigated soil genesis, classification, occurrence, class and general properties in relation to other peat soils. In a subsequent study, Ravikovitch (1945) studied the physical and chemical properties of the peat soils as a potential source of fertiliser for mineral soils.

Immediately after the drainage of the Hula swamps in the late 1950s, 100 soil cores were taken from the drained peat soils and various physicochemical properties, as well as their depths, were determined (Schallinger 1961, Schallinger & Ravikovitch 1962). Schallinger (1970) then analysed the humus chemistry of the peat soils and the role of polysaccharides in OM decomposition.

When cultivation problems became acute and the continuous subsidence of the peat soils became evident, an additional soil survey was conducted (Yaari-Cohen *et al*. 1971a, 1971b; Yaari-Cohen 1972). Further subsidence of the peat soils and recognition of the enormous complexity of organic soils necessitated a more detailed soil survey which yielded the first detailed soil map of the area (Israel Ministry of Agriculture 1986).
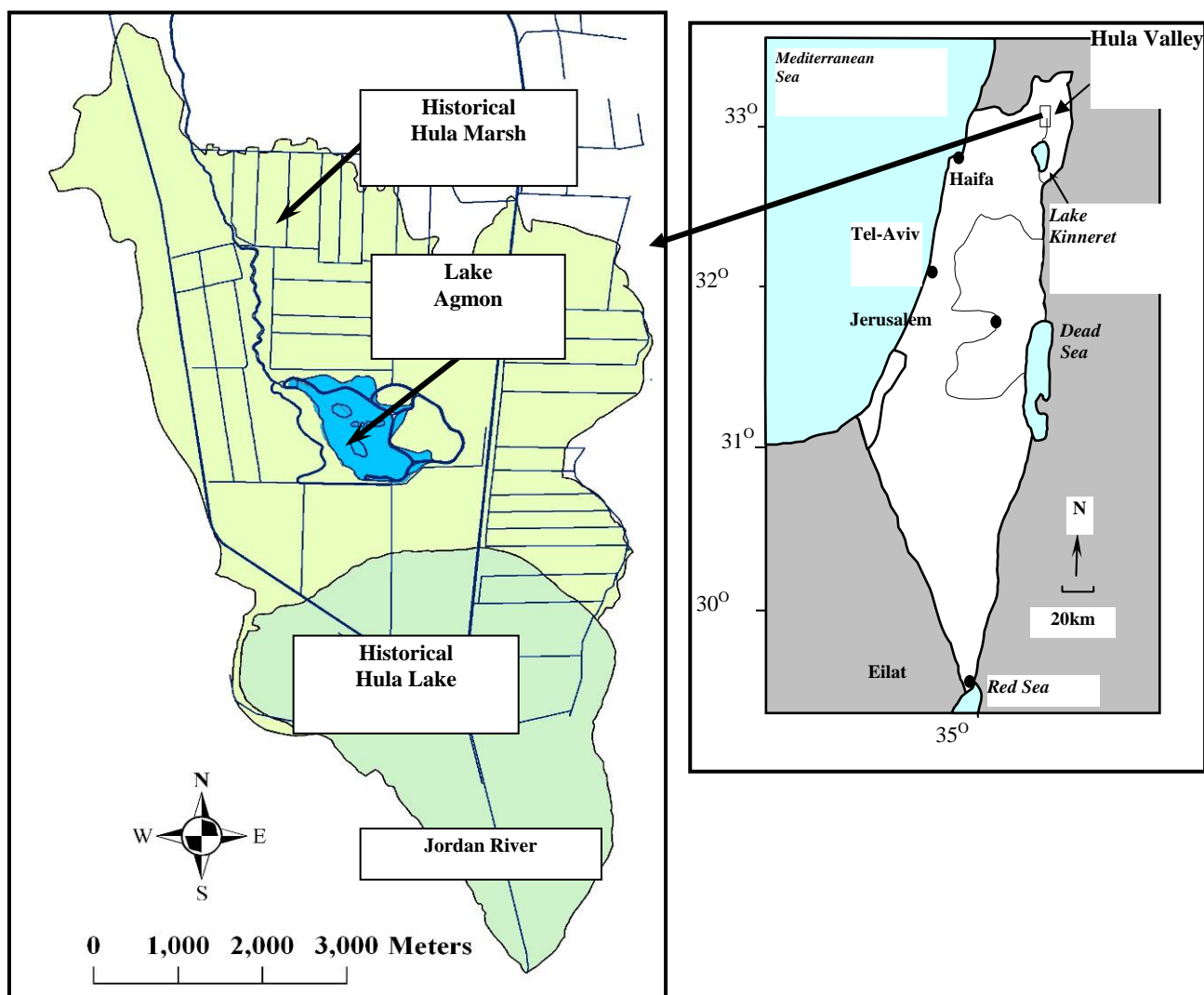

Figure 1. Maps showing the location of the Hula Valley area including Lake Agmon and the drainage canals (left), and the location of the Hula Valley within Israel (right).

STATUS OF THE PEAT SOILS

Before drainage
Before drainage, the soils of the Hula Valley were divided into two groups on the basis of their OM content (Ravikovitch 1936, 1945, 1992; Schallinger 1961; Schallinger & Ravikovitch 1962). The first group consisted of peat soils with 50–85 % OM, which were located within the boundaries of the drained swamps. The second group contained muck soils with 20–50 % OM. Further classification of the peat and muck soils used the following properties in decreasing order of importance: pH, base saturation, relative decomposition of OM, $CaCO_3$ content. The nature and amount of mineral layers within the peat soils was also taken into account.

The peat soils were further divided into two subgroups (Ravikovitch 1936, 1945, 1992). The first subgroup exhibited neutral pH, was fully base-saturated, and contained gypsum and various quantities of $CaCO_3$ (nil to common). Layers of organic-mineral material were often present within the soil profile. The second peat subgroup exhibited mild to strongly acidic pH values with low percentage base saturation, and contained gypsum with no or minimal quantities of $CaCO_3$. Layers of organic-mineral material and/or calcareous peat layers were quite common. The depth of the peat soils reached 8–9 m in some areas (Ravikovitch 1936, 1945; Schallinger & Ravikovitch 1962).

Ravikovitch (1945) and Schallinger (1961) suggested that the peat soils were formed by slow decomposition of plant material under mostly anaerobic conditions. Hence, the rate of humification of these soils was quite low and plant residues and structures were quite visible, even to the naked eye. The composition of the humic substances in the peat soils before drainage was described by Schallinger (1961, 1970), who found that humic acids comprised more than 30 % of the OM; this partially explained the low pH observed in some of these soils (Pimental *et al.* 1972).

The muck soils were mildly acidic with 70–90 % base saturation. They were often characterised by hydromorphic horizons, with or without lime. Layers of acidic peat and/or organo-mineral material with high levels of $CaCO_3$ were often observed. This soil type was interpreted as a mixture of decomposed swampy plant material with alluvium (Ravikovitch 1992).

After drainage
The significant subsidence of peat soils following drainage of the Hula Lake and surrounding swamps, which averaged 10 cm annually, prompted another soil survey to assess the influence of physicochemical processes on the subsidence rate (Yaari-Cohen *et al.* 1971a, 1971b; Yaari-Cohen 1972). In this survey, 35 cores, spaced 0.5 to 1.0 km apart across the entire extent of the drained peat soils (2,600 ha), were augered to a depth of 5–6 m and samples were taken for detailed physical, chemical and mineralogical analyses. A new soil classification was proposed, based on the following soil parameters: bulk density, *in-situ* soil moisture, OM content, $CaCO_3$ content, and common pedological observations. The field observations included soil colour (Munsell chart), field pH, consistency, approximate $CaCO_3$ content, and general observations of biota. The soils were classified into three groups, based on their bulk density and other soil variables (Table 1). A high to moderate correlation was found between the main soil classifier—bulk density—and other soil attributes such as soil moisture ($r = -0.95$), OM ($r = -0.87$), $CaCO_3$ content ($r = 0.7$) and residual volume after shrinkage ($r = 0.78$).

The peat and organic soils described in this classification scheme were further divided into four groups based on OM content and appearance (Yaari-Cohen 1972). The first group was defined as 'pure peat', originating mostly from *Cyperus papyrus* and other macrophytes, and characterised by a high fraction of partially decomposed but recognisable plant material (Table 2). Under anaerobic conditions, even the incomplete decomposition of plant material can take a considerable period of time. Upon oxygen penetration *via* roots or partial

Table 1. Summary of soil classification according to the parameters used by Yaari-Cohen *et al.* (1971a). BD: bulk density (g cm^{-3}); CEC: cation exchange capacity (cmol kg^{-1}); $CaCO_3$: % $CaCO_3$ by weight; OM: organic matter; shrinkage: % volume reduction during drying; % solids: percentage of solids by volume.

Soil type	BD	CEC	$CaCO_3$	OM	moisture	shrinkage	% solids
Peat	0.07–0.25	160–180	0–16	46–75	260–700	15–65	7–17
Peat-lime mineral	0.25–0.42	55–60	16–65	16–46	140–260	65–85	20–25
Lime-mineral (lake bed)	0.42–1.1	5–10	65–90	0–16	60–140	> 85	25–35

Table 2. Peat and organic soil types according to the classification by Yaari-Cohen (1972). OM: organic matter.

decomposition stage	depositional environment	'Pure peat'	Soil containing > 30 % OM TYPE OF MINERAL MATERIAL			Soil containing 10–30 % OM TYPE OF MINERAL MATERIAL			Soil containing < 10 % OM TYPE OF MINERAL MATERIAL		
			LAKE DEPOSITS	FINE ALLUVIAL	COARSE ALLUVIAL	LAKE DEPOSITS	FINE ALLUVIAL	COARSE ALLUVIAL	LAKE DEPOSITS	FINE ALLUVIAL	COARSE ALLUVIAL
peat contains recognisable plant material	*in situ*	pale porous peat	pale peat with marl	massive pale peat		pale marl with peat	clayey pale grey peat				
	alluvial	pale layered peat	pale layered peat with marl	pale clayey layered peat		pale marl with layered peat	clayey layered pale grey peat				
	in situ, alluvial	red peat									
first stage of OM oxidation	*in situ*	dark porous peat	dark peat with marl	massive dark peat		dark marl peat	dark clayey peat				
	alluvial	dark layered peat	dark peat with layered marl	dark peat with clayey layer	Sandy peat Loamy peat	dark marl layered peat	dark clayey layered peat				
advanced oxidation		decomposed peat	decomposed peat with lake sediments	decomposed peat with clay	decomposed peat with sand or loam	organic marl	organic clay	organic sand	swampy marl	swampy sand and loam	hydromorphic sand and loam

drying, iron oxides precipitate, colouring the soil with strong red to orange hues. In sites where oxygen penetration through the soil had been continuous, the plant material had decomposed significantly, turning the soil into a dark blackish mass (Table 2). The second group of peat soils contained more than 30 % organic matter and significant fractions of mineral matter originating from lake deposits or fine-textured alluvial sediments. This group was further subdivided into soils with recognisable plant material *versus* more oxidised soils with dark massive appearance. The third group contained 10–30 % OM, with or without recognisable plant material; and the fourth group consisted of soils developed on swampy marl substrate with less than 10 % OM and hydromorphic soils that contained less than 10 % OM with no recognisable plant residues (Table 2).

The source of the mineral material in these organic-mineral soils was calcareous silt deposited in Lake Hula and alluvial material carried by winter floods. When the suspended load was light it was deposited on the swamps, creating layered organic-mineral soils. If the flooding was strong enough to transport some of the swamp material, this would later be deposited on the shores of the old Hula Lake, creating a highly heterogeneous mixture of organic and mineral soil materials. On several occasions, the swampy area was completely submerged by flooding, and this turned the swamp into a shallow lake resulting in the deposition of a clayey layer. Once the water receded, the swampy conditions returned, and further organic soil horizons formed on top of the clayey layer. Oxygen penetration into the organic-mineral material resulted in precipitation of iron oxides and hydroxides, producing a wide spectrum of hues. On the basis of these observations and interpretations, Yaari-Cohen *et al.* (1971a) identified a total of 41 soil types in ten mapping units across the Hula Valley.

In summary, Yaari-Cohen (1972) suggested that the degree of peat soil development is a function of swamp conditions, vegetation type, anaerobic *versus* aerobic conditions, amount and type of alluvial material deposited in the swamps, and seasonal episodes of flooding and drying. The combination of these depositional factors determined the rate of decomposition of the buried plant material and the rate of humification as additional classification characteristics (Table 2). Yaari-Cohen (1972) also concluded that the type of soil formed in the Hula Valley before drainage depended upon the location of the site in relation to the swamps, the old Hula Lake, and the internal drainage system of the valley.

Several researchers have noted the susceptibility of the Hula Valley peat soils to cycles of drying and rewetting, which result in irreversible hydrophobicity. This, in turn, reduces water retention capacity and the amount of available water (the difference between water content at 33 kPa and 1500 kPa) (Schallinger 1970, Ravikovitch 1992) (Table 3). Drying and wetting cycles occurred even before the valley was drained, during seasonal flooding and drying, especially in extremely wet and/or dry years. This phenomenon has become quite prevalent since drainage because the position of the water table, controlled by the drainage canals, has fluctuated widely over the years due to inadequate management practices.

One of the major pedological features of the drained peat soils was the continuous subsidence of the soil surface. According to the soil survey of Yaari-Cohen *et al.* (1971a, 1971b), performed in the early 1970s, the subsidence of peat soils resulted from the combined effect of loss of matter and loss of volume These authors attributed the loss of matter to mineralisation of OM, frequent internal conflagration, and wind erosion. The loss of volume was additionally generated by shrinkage, structural collapse, settlement of layers above the mean water table, and consolidation of layers below it.

Table 3. Impact of drying on the water retention capacity of peat soils. Values are water contents (% w/w, modified after Schallinger 1970). Available water is the difference in water content (%) between field capacity and wilting point.

Depth (cm)	PEAT SOIL			PEAT SOIL AFTER DRYING		
	field capacity (33 kPa)	wilting point (1500 kPa)	available water	field capacity (33 kPa)	wilting point (1500 kPa)	available water
0–25	89	61	28	72	55	17
25–50	190	83	107	92	71	21
50–100	317	200	117	171	128	43
100–150	352	234	118	164	129	35
150–200	346	219	129	121	97	24

SOIL CLASSIFICATION AND MAPPING DURING THE 1980s

In the mid-1980s, the soil subsidence rate increased and the agro-technical problems intensified, necessitating a new soil survey and mapping of soil units. Some 1465 boreholes (depth 120 cm) were drilled across an area of 3650 ha. The soils were described in the field and classified according to diagnostic horizons observed at depth 30–90 cm. Eighteen selected sites were excavated and sampled for additional laboratory analyses (Israel Ministry of Agriculture 1986). Because there was no established classification scheme for peat soils that had been drained and had undergone the changes described above, a special classification method, based partly on the American soil taxonomy system (Soil Survey Staff 1975) and the pedological investigation of Yaari-Cohen (1972), was adopted (Figure 2).

This latest soil classification divided the Hula soils into five major units, based mainly on their parent material. The classification scheme consisted of five groups: (1) peat soils that had developed from swampy vegetation, mainly *Cyperus papyrus*; (2) organic-mineral soils developed along the margins of the swamp and formed by a mixture of plant residue and alluvium; (3) calcareous soils developed from marl-lacustrine deposits of the old Hula Lake; (4) gley soils found mainly along the lake shore and around ponds in the swamps, characterised by a low redox potential that dictates their odour and colour; and (5) soils that developed outside the old lake-swamp complex and are not unique to the Hula Valley, including various Inceptisols, Vertisols and Mollisols. Further classification of Groups 2 through 4 was based mainly on texture and depositional appearance in the field.

Parent material/soil classification
- Marl
- Gromosol
- Gleyey soils
- Basaltic alluvium colluvium
- Brown Alluvium
- Peat
- Basaltic protogromosol
- Organic-mineral soils
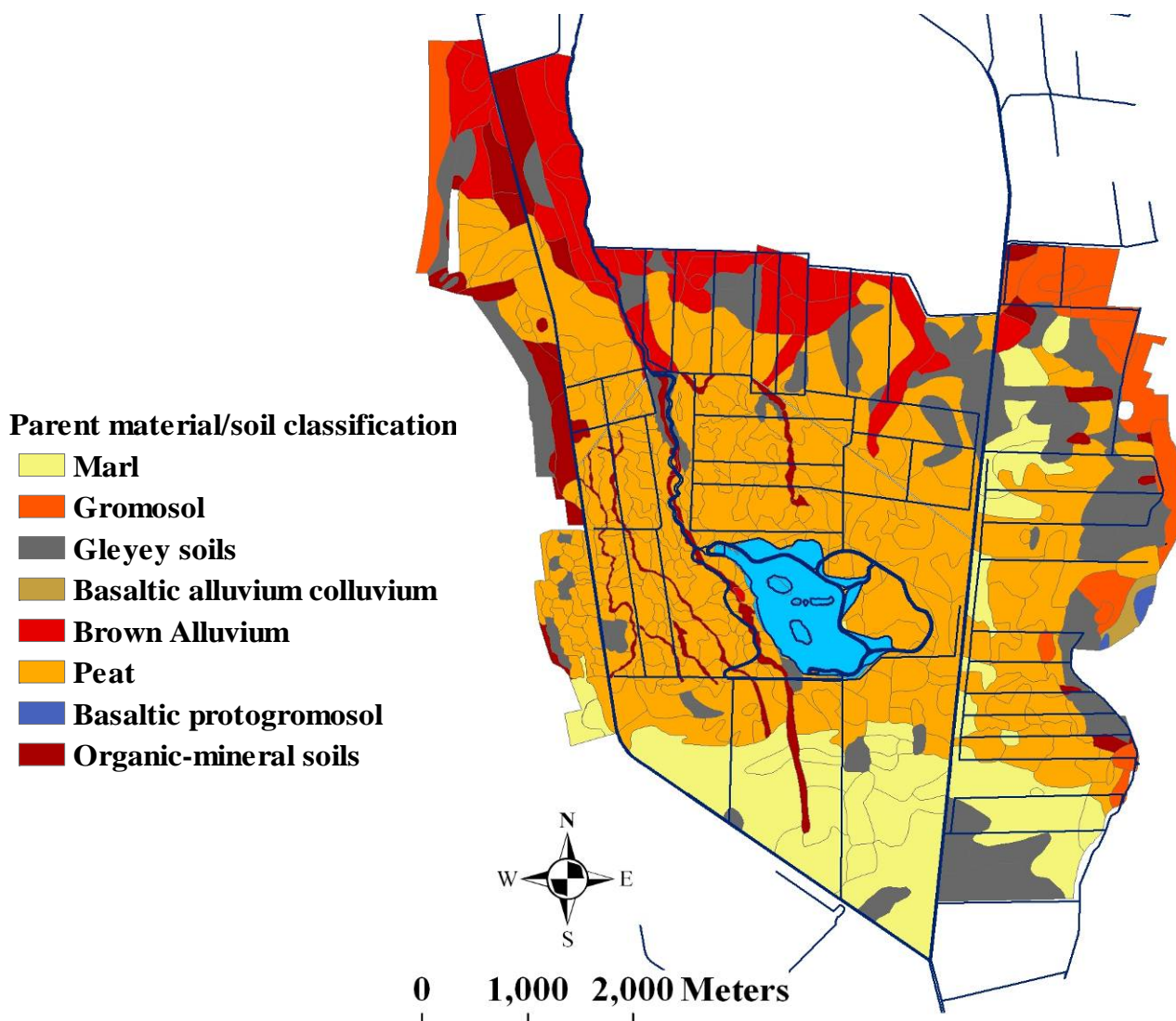
N
W E
S

0   1,000   2,000 Meters

Figure 2. Soil classification map of the altered Hula Valley wetlands, modified from Israel Ministry of Agriculture (1986).

The peat soils of the Hula Valley identified in this survey were predominantly Histosols (~1860 ha) that were subdivided into four major groups, three of which appear in the US Soil Taxonomy, namely: (1) Medifibrists, (2) Medihemists, and (3) Medisaprists. In the Medifibrists, the cellular structure of plant remnants could still be seen in the field. In the Medihemists, plant decomposition had reached an advanced stage but plant remnants were somewhat recognisable in the field; whereas the Medisaprists were the most decomposed soils, whose fibric material could not be recognised in the field. In the Hebrew terminology, these major groups are termed *Kavlor*, *Kavlum* and *Kavlutz* respectively. The role of internal combustion in Histosol pedogenesis was recognised by the Israeli classification system and a fourth major soil group termed 'Conflagrated Histosols' was created.

Using the Israeli soil taxonomy system, each of these four major groups was further divided on the basis of the occurrence and amount of $CaCO_3$, which resulted in Medifibrists, Medihemists, Medisaprists and 'Conflagrated Histosols' without lime, with minimal lime, and with lime. The occurrence and content of $CaCO_3$ also controlled the pH of the Histosols. Following drainage of Hula Lake and its wetlands, some of the Histosols without lime were highly acidic (pH <4.0). The soil surveyors (Israel Ministry of Agriculture 1986) attributed the acidity to oxidation of pyrite (FeS_2), which produces sulphuric acid. When $CaCO_3$ was present in the soil profile, the products of the FeS_2 oxidation formed gypsum. The low pH occasionally measured in these peat soils was also explained by the release of humic acids (Pimental *et al.* 1972). During the summer of 2009, we collected 90 topsoil samples and measured electrical conductivity, pH and NO_3 among other soil attributes. There was a high correlation between electrical conductivity and nitrate (r = 0.94, P <0.001), as well as a moderately high negative correlation between pH and nitrate (r = -0.62, P <0.001). The peat soil samples that exhibited low pH (5.0–3.8) were all characterised by extremely high nitrate concentrations (>10,000 mg kg^{-1}). This finding indicated that the occasional acidity of the peat soils is probably influenced by more than one process and may be due to pyrite oxidation, release of humic acids and/or nitrification. This premise can be tested by determining the pe+pH, which defines the redox status of the soil system, coupled with *in-situ* measurements of nitrification rates during drying and wetting cycles.

The soil survey published in 1986 showed that the top 30 cm of the peat soils had been homogenised by ploughing and further oxidation of soil OM had occurred. The topsoil horizon exhibited a fairly uniform texture that varied between sandy and silty loam. On average, this layer contained 10–30 % OM, compared to 40–60 % before drainage. The second soil horizon used as a diagnostic horizon for the soil classification, at depth 30–90 cm, was less homogeneous but also exhibited profound loss of OM over the years. In 1945, this layer contained 50–70 % OM (Ravikovitch 1945); this figure declined steadily after reclamation of the area, to 30–50 % in 1970 (Yaari-Cohen *et al.* 1971a, 1971b; Yaari-Cohen 1972), and 25–35 % in 1985 (Israel Ministry of Agriculture 1986). Further decline in the OM content of the deeper diagnostic layer was observed during soil sampling in 2000 (17–36 %), although the decline varied widely amongst the various soil groups (Table 4) (Litor *et al.* 2003). Moreover, recent soil sampling during the summer of 2009 in 90 topsoil horizons across the Hula Valley showed that the top layer contained 13–24% OM on average, which is a clear indication of further decline in OM content over time (Table 4).

Clearly, from the data presented above, the Histosols in the Hula Valley have not reached a steady state. Information on physicochemical characteristics gleaned from previous studies is of limited use because of the radical changes that have occurred since the 1950s and continue to occur today. The most profound transformations of the Hula Valley Histosols are an increase in pH and a decrease in OM content, which have led to increased bulk density and hydraulic conductivity. Major cracks developed in the Histosols following drying of the wetlands. The network of macropores now regulates the lateral and vertical preferential flow and solute transport observed in certain areas (Litor *et al.* 2006, 2008, Sade *et al.* 2010).

Table 4. The distribution of organic matter content (g kg^{-1}) in soils collected across the Hula Valley. SE: standard error.

	n	mean	SE	range
Sampling at 0–30 cm, summer 2009				
deep peat	48	22	1.1	8–38
shallow peat	24	24.8	1.8	7.2–41.6
marl	18	13	1.6	6.1–29.5
Sampling at 50–90 cm, summer 2000				
deep peat	12	36.2	2.1	14–71
shallow peat	13	31.9	5.9	11–58
marl	28	17.4	4.5	8.2–30.6

THE FEASIBILITY OF SOIL MAPPING

The soil map published by the Israel Ministry of Agriculture (1986) was used in the early 1990s for planning the creation of Lake Agmon and transforming the least fertile soils into wetlands. In 1998 we selected eleven sites, located on a north-south transect across the valley, which should have represented the most typical Medifibrists, Medihemists, and Medisaprists according to the published map (Litaor *et al.* 2004). We drilled 33 soil cores at these sites to assess the phosphorus geochemistry and to quantify phosphorus mobility as a consequence of the elevated water table around Lake Agmon. None of the soil cores sampled met the taxonomic requirements for Medifibrists and/or Medihemists. We concluded that the soils had been further oxidised, homogenised by ploughing, and decomposed, so that fibrist and hemist type materials could no longer be found at shallow depth (0–200 cm). Hence, the published map (Israel Ministry of Agriculture 1986), which was based on a pedological analysis of the diagnostic horizons between 30 and 90 cm, did not provide up-to-date information. Furthermore, the continuously changing conditions of the Histosols in the Hula Valley made a new soil mapping campaign inappropriate.

We propose that future soil mapping, if this is deemed necessary, should adopt a probability approach based on the acceptance of uncertainty and the possibility of making classification errors. For example, modelling the values of continuous soil attributes to yield probability maps which summarise many realisations of the pertinent attributes, combined with computation of the uncertainty at unsampled locations, will provide more useful information on agricultural and/or environmental aspects of the soils than the general information that can be deduced from a conventional soil survey.

Soil maps attempt to capture spatial variability within an accepted framework of pedogenesis. Because the spatiotemporal changes within the Hula Valley soils are too great, the general information that can be gleaned from the soil map has little validity over time in this instance. Moreover, the information for the *probability* maps should be derived from pedo-transfer functions (e.g. soil colour) as surrogate variables, rather than laborious and expensive measurements of soil attributes such as phosphorus sorption capacity (Litaor *et al.* 2003). These maps can be easily drawn with the aid of geographical information system (GIS) software coupled with stochastic simulation and/or geostatistical techniques.

CONCLUDING REMARKS

The altered wetland soils of the Hula Valley have undergone several major land use changes that strongly affected their physicochemical characteristics, namely: complete drainage of the old Hula Lake and swamps; intensive cultivation of the drained soils with concurrent increased nutrient leaching to the waterways; reduction in soil fertility; and increased agro-technical problems followed by farmland abandonment. Subsequently, the least fertile soils were re-flooded, transforming them into a shallow lake and wetland that are currently being used as a bird sanctuary and a centre for ecotourism. The re-flooding has elevated the water table in the adjacent soils so that it is close to the surface, resulting in considerable redox change from aerated to anoxic. The organic soils have not reached a new steady state. Recent and future adverse processes may, therefore, lead to new problems such as increased phosphorus loss and increased soil salinity. Due to the frequent land use changes, previous soil maps have become inaccurate. For future land use planning and management, we recommend producing probability maps instead of conducting new soil surveys and mapping.

REFERENCES

Dimentman, C., Bromley, H.J. & Por, F.D. (1992) *Lake Hula: Reconstruction of the Fauna and Hydrobiology of a Lost Lake*. The Israel Academy of Sciences and Humanities, Jerusalem, Israel, 170 pp.

Israel Ministry of Agriculture (1986) (*The Hula: a Soil Survey Report*). Ministry of Agriculture/ Water Commissioner, Department of Soil Conservation and Drainage, Lake Kinneret Authority, 45 pp. (in Hebrew).

Litaor, M.I., Eshel, G., Reichmann, O. & Shenker, M. (2006) Hydrological control of phosphorus mobility in altered wetland soils. *Soil Science Society of America Journal*, 70, 1975–1982.

Litaor, M.I., Eshel, G., Sade, R., Rimmer, A. & Shenker, M. (2008) Hydrogeological characterization of an altered wetland. *Journal of Hydrology*, 349, 333–349, doi: 10.1016/ j.jhydrol.2007.11.007.

Litaor, M.I., Reichmann, O., Auerswald, K. & Shenker, M. (2004) The geochemistry of phosphorus in an altered wetland. *Soil Science Society of America Journal*, 68, 2078–2085.

Litaor, M.I., Reichmann, O., Belzer, M., Auerswald, K., Nishri, A. & Shenker, M. (2003) Spatial analysis of phosphorus sorption capacity in a

semi-arid altered wetland. *Journal of Environmental Quality*, 32, 335–343.

Pimental, R., Natav, Y. & Avnimelch Y. (1972) (*pH Survey of the Hula Soils*). Publication 173, The Laboratory of Fertilizers and Soils, Technion, Haifa, Israel, 42 pp. + 18 maps (in Hebrew).

Ravikovitch, S. (1936) Report on the Investigation of the Chemical Composition and Properties of the Huleh Soils in the Concession Area. In: *General Report on the Huleh Basin—Reclamation, Drainage and Irrigation*, Rendel, Palmer & Tritton Consulting Engineers, London.

Ravikovitch, S. (1945) (The peat soils and enriched organic matter soils of the Hula Valley). *Agricultural Reports*, 1, 23–54 (in Hebrew).

Ravikovitch, S. (1992) (*The Soils of Israel: Formation, Nature and Properties*). Hakibbutz Hameuchad Publishing House, Tel Aviv, Israel, 489 pp. (in Hebrew).

Reifenberg, A. & Moshicky, S. (1941) Palestine peat in relation to other peats. *Soil Science*, 51, 173–180.

Sade, R., Litaor, M.I. & Shenker, M. (2010) Evaluation of groundwater and phosphorus transport in fractured altered wetland soils. *Journal of Hydrology*, 393, 133–142, doi:10.1016/j.jhydrol.2010.02.032.

Schallinger, K.M. (1961) *Beneficiated Peat and Its Agricultural Value*. The Natural University, Agricultural Investigation, 115 pp.

Schallinger, K.M. (1970) (*Investigations of the Agricultural Problems Concerning Peat Soils of the Hula Valley*). Report number 673, Volcani Institute for Agricultural Research, Bet Dagan, Israel, 1–33 (in Hebrew).

Schallinger, K.M. &. Ravikovitch, S. (1962) Organic soils in the Hula Valley, occurrence, classes, and properties. *Bulletin Research Council of Israel*, Section 9, 11G, 163–164.

Shaham, G., Minzker, H. & Kennaan, G. (1990) (*Alternative Utilization of the Hula Lands – a Feasibility Study*). Israel Ministry of Agriculture, Hula Committee, 47 pp. (in Hebrew).

Shoham, D. & Levin, I. (1968) Subsidence in the reclaimed Hula swamp area of Isreal. *Israel Journal Agriculture Research*, 18, 15–18.

Soil Survey Staff (1975) *Soil Taxonomy: a Basic System of Soil Classification for Making and Interpreting Soil Surveys*. USDA-SCS Agricultural Handbook 436, US Government Printing Office, Washington DC, 779 pp.

Tsipris, J. & Meron, M. (1998) Climatic and hydrological aspects of the Hula restoration project. *Wetland Ecology and Management*, 6, 91–100.

Yaari-Cohen, G. (1972) (*Survey of the Drained Peat Soils of the Hula Authority Farm*). Ministry of Agricultural and the Water Commissioner, Department of Soil Conservation and Drainage, Hakiria, Tel Aviv, 171 pp. (in Hebrew).

Yaari-Cohen, G., Paldi, H., Moses, G. & Harpaz, A. (1971a) (*A Survey of the Peat Soils in the Hula-Valley, Israel, Part I*). Ministry of Agriculture, Department of Soil Conservation and Drainage, Kyriat Shemona, Israel, 112 pp. (in Hebrew).

Yaari-Cohen, G., Paldi, C., Moses, G. & Harpaz, A. (1971b) (*A Survey of the Peat Soils in the Hula-Valley, Israel, Part II—Appendices*). Ministry of Agriculture, Department of Soil Conservation and Drainage, Kyriat Shemona, Israel, 78 pp. (in Hebrew).

_____

Author for correspondence:
Professor Iggy Litaor, Tel-Hai College and MIGAL Laboratory, Upper Galilee 12210, Israel.
Tel: +972 48181725; Email: litaori@telhai.ac.il