Research Findings

Conclusions from the Permanent Plot Experiment at Gilat, Israel: Long-Term (35-Year) Effects of Manure and Fertilizer on Crop Yield, Soil Fertility, N Uptake, and Solutes Leaching in Soil*

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Abstract

Long-term application of fertilizer and manure may change soil fertility, crop yield, N uptake efficiency and nitrate and chloride leaching to underground water. The objectives were to quantify those aspects in a long-term (35-year) permanent plots field experiment in a typical arid zone (~250 mm rain) soil, and suggest fertilization and manuring regimes leading to reduced aquifer pollution by nitrate and chloride without compromising crop yield and soil sustainability. Results proved that mineral-N application exceeding plant demand leached, subject to recommended irrigation plus rainfall, below 4 m thus becoming a potential underground water pollution hazard. Leaching was significantly reduced by partially replacing fertilizer-N by manure-N, with negligible adverse effect on crop yield. Under ample manure (M2) and mineral N (N3) supply (treatment M2N3),

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the estimated cumulative (35-year) NO_3^- leaching was 557 g N m^{-2} and the corresponding Cl$^-$ leaching 4,097 g Cl$^-$ m^{-2}. In treatment M2N0 the corresponding leaching was 0 and 4,135 g m^{-2}. The cumulative solute leaching depth was estimated to be 66 m in treatment M2N3 (that gave maximum fruit and dry matter yield) and 125 m in treatment M0N0 (minimum fruit and dry matter yield). Soil cultivation and cropping for 35 years had negligible effect on the plants response to fertilizer level and on the soil mineralogical composition.

Keywords: Loess soil; manure; soil organic nitrogen; P K availability in soil; N uptake; leaching; dry matter production; transpiration; irrigation.

Introduction
The Gilat long-term fertilization experiments (LTFE) was established in Israel in 1961 by the Volcani Institute of Agricultural Research, to provide a scientific basis to the transition from rain-fed to irrigation-fed agriculture in the southern, arid part of the country. This area is characterized by 200-300 mm rain (all in winter), a loessial soil and good quality water (EC < 1.2 dS m^{-1}) imported from the north. The objectives of the LTFE were to develop and test new fertilization regimes under conditions of controlled irrigation in arid climate; adopt new cash crops grown under irrigation; study the plants short and long-term response to fertilizer and manure N; and to improve and calibrate soil tests to evaluate nutrients availability in soil. The experiment prevailed until 1994 and involved 35 growing seasons of the major crops grown in the area. The historic season-by-season crop and soil data of all the 16 N x Manure treatments was compiled recently and stored on the web (Bar-Yosef and Kafkafi, 2016). This report focuses on the long-term fertilizer and manure effects on crop fresh and dry yield, mineral and organic N balance in soil, N uptake efficiency, and nitrate and chloride leaching to underground water. Results concerning the annual crop response to N and the interrelationships with other nutrients in soil are outside the scope of this article.

Materials and methods
Soil and manure properties
The experimental site was Gilat Experiment Station (35°E, 30°N). The soil is loessial (Typic Haplargid, Calcic Haploxeralf) and its chemical properties are summarized in Table 1. The soil volumetric water content at air dryness and field capacity are 3.5% and 23%, respectively.

The mean dry matter of the dairy manure contained 40% organic matter (dry digest), 1.8% N, 0.6% P and 2.5% K. The mean contents of the dry matter city refuse compost were 45% organic matter, 1.5% N, 0.35% P and 0.5% K.

Growth conditions, treatments and agro-technique
The time-averaged monthly mean air temperatures in January to December were 11, 13, 16, 21, 24, 29, 32, 32, 29, 25, 18 and 13°C, respectively. The cumulative (35-year) irrigation, rainfall, and seasonal evaporation from class A pan were 16,000, 6,676, and 22,900 mm, respectively. The experimental design was four mineral-N x four manure levels, replicated six times in random blocks. The N was applied until 1985 as ammonium sulfate and later (as drip replaced sprinkle irrigation) as ammonium nitrate supplied via the water (average Na and Cl concentrations 7.0 and 7.5 mM, respectively). The manure treatments were control, two levels of commercial dairy manure, and one level of city refuse compost. All treatments received identical superphosphate and KCl doses before seeding and same irrigation rate. More details can be found in Bar-Yosef and Kafkafi (2016). The irrigation was applied to replenish class A pan evaporation (EV$_a$) multiplied by a time dependent crop coefficient. The major crops, grown in rotation were corn, cotton, onion, carrot, potatoes, processing tomatoes, pepper, lettuce, broccoli, celery, Chinese cabbage and muskmelon. The yield of 15 m row length of two centered rows was cut and measured for fresh and dry weight. Plant tissue was analyzed by digesting dry (60°C) ground tissue sample with $H_2SO_4 + H_2O_2$ for N, P, K, Na determination and with $HNO_3 + HClO_4$ for S analysis. N, P and S were determined by auto-analyzer, K and Na by flame

Table 1. Some soil properties of the Gilat soil.[1]

Layer	Horizon	pH	EC 1:1	CaCO$_3$	Clay	Silt	Sand		Org C	Org N
							Fine	Coarse		
cm			*dsm^{-1}*	--%--						
0-25	Ap	8.2	1.2	18.6	16.5	33.2	46.3	4.0	0.70	0.075
25-40	B1	8.2	0.9	28.0	22.0	39.9	35.4	2.7	0.77	0.078
40-80	B2	8.3	0.7	28.9	23.0	43.2	30.4	3.4	0.73	0.075
80-120	B3	8.3	0.6	21.1	25.9	38.9	30.6	4.6	0.67	0.084

Note: [1]The data was derived from Feigin and Hidesh (1969). The untreated soil mineralization potential at field capacity conditions is 1.5% of the soil organic N per year (0-20 cm soil layer), which is equivalent to ~30 kg N ha^{-1}Y^{-1} (Feigin and Sagiv, 1988). The soil volumetric water content at air dryness and field capacity are 3.5% and 23%, respectively. The mineral composition of the soil is quartz (45-60%), clay minerals + micas (10-20%), plagioclase (10%), K-feldspare (10%) and calcite (10%). The major clay mineral is illite-smectite (montmorillonite). The soil chemical composition is 61% SiO_2, 7% Al_2O_3, 3% Fe_2O_3, 11% CaO, 1.7% MgO and 1.2% K_2O. All the above mentioned results were very similar (within the range of analytical error) in the 0-20 and 20-40 cm soil layers. The cation exchange capacity (CEC) of the soil is 9.7 - 10.9 mmol$_c$ 100 g^{-1}, the range covering the time and treatments span of the experiment. Calcium (Ca) and potassium (K) constitute ~50% and ~15% of the CEC, respectively. The source of all these results is Sandler *et al.* (2009).

photometer and Cl by chloridometer. Soil samples were dried at 40°C and ground to pass through a 2 mm sieve. Soil tests included 1:1 soil: water extracts (unless otherwise stated), soil extracts by $CaCl_2$ and $NaHCO_3$, and total N (Kjeldahl-N), all performed by standard methods (Sparks, 1996).

Computations

Dry matter (DM) was used to estimate transpiration (T) in treatment i (Hanks and Ashcroft, 1980):

$$T_i = T_{max} \, DM_i / DM_{max} \qquad [1]$$

T_{max} was evaluated as 0.5 EV_a (transpiration during daylight hours only) and DM_{max} is DM in the treatment that gave maximum yield in a specific year. The annual mineralization (N_{min}, g m^{-2}) was calculated from two organic-N pools: the soil indigenous organic-N (SON) and manure organic-N (MON).

$$N_{min} = 0.02 \, SON + 0.15 \, MON \qquad [2]$$

It was assumed that the MON pool that was not mineralized in one year became SON (Bar-Yosef, 1999), and 5% of the N consumed by plants returned to the soil as SON.

The water head available for solute leaching (L) was calculated according to [3]:

$$L = I + R - T - E \qquad [3]$$

Here I and R are annual irrigation and rainfall rates, and T and E cumulative transpiration and annual evaporation from the soil, respectively. The E was estimated as 120 mm y^{-1}, which is ~50% of the mean annual precipitation at the experiment site.

Ions and water mass balance in soil is described in Equation [4]. The IL is the ion quantity leached below 420 cm (g m^{-2}); IA is the cumulative (35 year) ion quantity added to the soil. In the case of nitrogen, it is fertilizer-N + mineralized-N, assuming

that all the ammonium in the soil solution is nitrified and that denitrification is negligible. IU is the cumulative uptake by plants, and IS the quantity accumulated in the 0-420 cm soil profile (IS_{end} - $IS_{initial}$).

$$IL = IA - IU - IS \qquad [4]$$

Mineralized-N was estimated from the organic-N mineralization rate, computed from the mineralization model, Equation [2].

The water head available for solute leaching (L) was calculated according to Equation [3] above. The total DM production in a certain treatment (used to estimate T, Equation [1]) is the sum of annual DM yields over the experiment (Table 2).

The solutes leaching depth (h, cm) was estimated from L by assuming Equation [5], and that salts displacement is instantaneous and driven by piston flow.

$$h = L / (\theta_{fc} - \theta_i) \qquad [5]$$

The initial water content (θ_i) was assigned a value of 0.12 v/v, which is ~50% of the soil's field capacity (θ_{fc}, 0.23 v/v). The θ values must be uniform along the entire soil profile.

Statistics

The compiled data set (Bar-Yosef and Kafkafi, 2016) contains only treatment means; the historic per replicate results

were unfortunately lost and consequently ANOVA and least significant difference (LSD) tests could not be performed on presented data. Exceptions were the 1993 and 1994 carrot experiments where all replicate results were available. The statistical analysis of the fresh and dry carrot yields revealed that the ratio [LSD] / [treatments mean] was 0.10±0.02 and 0.15±0.01, respectively. Since experimental conditions have not changed along the experiment, the above ratios may also represent the ratio in previous experiments and if the treatments mean is known, the LSD can be approximated.

Results and discussion

The experimental results are confined to 6 (out of the 16) treatments: M0N0 (no manure, no N-fertilizer), M0N3 (no manure, 789 g fertilizer-N m^{-2} in 35 years), M2N0 (984 g organic-N m^{-2} in 35 years, no mineral N), M1N3 (328 g organic-N m^{-2}, 789 g fertilizer-N m^{-2}), M2N3 (984 g organic-N m^{-2}, 789 g fertilizer-N m^{-2}) and RN3 (296 g organic-N m^{-2}, 789 g fertilizer-N m^{-2}).

Crop yield and dry matter production

Yields varied in the annual experiments from high to low depending on treatment (for some examples see Table 2). Usually a direct relationship existed between annual fresh fruit yield and plant dry matter production (not presented). The manured, unfertilized plots (M2N0) gave a yield that was somewhat lower than the manured, fertilized plots (M2N3), but close to the

Table 2. Fresh yield of representative treatments and total (35-years) dry matter production.

Year	Crop	Treatment					
		M0N0	M0N3	M2N0	M2N3	M1N3	RN3
		--------------------*Fresh crop yield (kg m^{-2})*----------------------					
1963	Potato	2.55	3.80	3.00	3.90	3.90	3.85
1978	Sweet corn	0.27	2.06	2.38	2.80	2.53	2.27
1981	Processing tomato	6.16	4.90	7.95	7.58	7.34	7.58
1987	Muskmelon	1.44	2.58	2.92	2.92	2.76	3.65
1994	Carrot	5.86	8.42	7.93	9.00	8.66	9.29
		--------------------*Total dry matter (kg m^{-2})*----------------------					
1961-1994	All crops	9.6	21.5	19.4	25.2	23.0	23.7

un-manured, fertilized plots (M0N3). Plots fertilized at the N3 level responded positively in fresh yield when the manure level increased from M0 to M1 and M2, but the enhanced yield was crop specific: negligible in potato and muskmelon, moderate in carrot (8.4, 8.7 and 9.0 kg m^{-2}) and considerable in sweet corn (2.1, 2.5 and 2.8 kg m^{-2}) and processing tomatoes

(4.9, 7.3 and 7.6 kg m^{-2}). The response in cumulative dry matter production (all crops, 35-years) was 21.5, 23.0, 25.2 kg m^{-2}, all respectively. City refuse compost (R) affected yield similarly to manure level M2. The mechanisms by which manure increased yield at the N3 level could not be explicitly determined in this experiment.

Ion distribution in soil (0-420 cm) at the end of the experiment

After last harvest (September 1994), the soil was sampled to depth of 420 cm, and major ions were determined in 1:1 soil: water extract. The results are depicted in Fig. 1. The nitrate (NO_3) profile (Fig. 1A) was similar in all treatments, but concentration at each depth increased with increasing N application rate. In all treatments, NO_3 concentration in the 80-160 cm soil layer was low, and no clear concentration peaks could be observed in the accumulation zone 180-400 cm. In the exceptional N3 treatments nitrate tended to accumulate in the 180-300 cm soil layer. The nitrate amount in the 0-420 cm layer was 8-16% of the mineral N that was added to soil.

Chloride was added in all treatments at the same rate. Assuming no considerable differences in Cl uptake by plants, different Cl$^-$ concentration profiles (Fig. 1B) could stem only from different leaching patterns, caused by differential transpiration by plants exposed to diverse fertility treatments. Indeed, in fertilized plots (high transpiration, less deep leaching) Cl$^-$ concentration in the 40-90 and 300-400 cm soil layers was higher than in unfertilized plots (deep leaching). This effect was even more pronounced in the EC profiles (Fig. 1C), except treatment M2N3 that had unexpectedly low EC
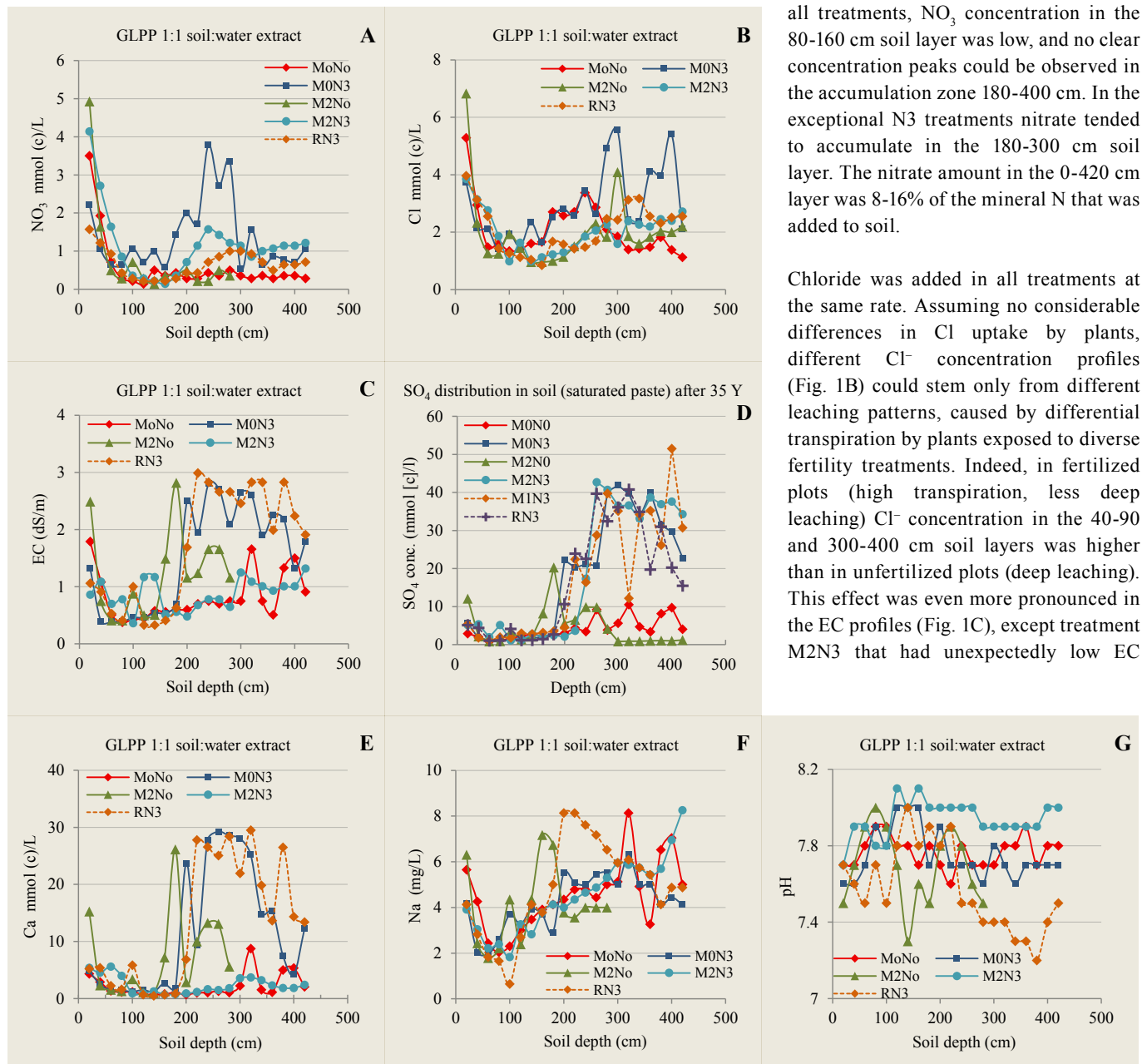

Fig. 1. Distribution of the main ions in the soil profile (0-420 cm) at the end of the experiment (35 years) in representative treatments. 1:1 soil: water extract (except saturated paste in SO$_4$). NO$_3$ (A), Cl (B), EC (C), SO$_4$ (D), Ca (E), Na (F), pH (G).

values. As in the case of nitrate, no clear peaks were found in the Cl and EC profiles, but unlike nitrate the Cl- accumulated in the 200-400 cm soil layer.

Sulfate was applied equally to all treatments through the supply water and in superphosphate, and differentially (until 1986) as ammonium sulfate (AS). In plots that were fertilized with AS, the sulfate accumulated in the 200-400 cm soil layer, while in treatment N0 the concentration of SO_4 in the entire soil profile was low (Fig. 1D). Below a depth of 200 cm the water soluble SO_4 concentration was tenfold greater than Cl concentration. The similarity between the soil SO_4 and Ca profiles (Fig. 1E) indicates that the sulfate concentration in treatments receiving high N (N3) were controlled by gypsum solubility. Since the $CaSO_4$ solubility product (K_{sp}) is $10^{-4.64}$ (Lindsay, 1979), the SO_4^{2-} solution concentration is expected to be between 9.6 and 25 mmol L^{-1}. The higher value is expected if Ca^{2+} concentration is governed by soil $CaCO_3$ (pH 8) and PCO_2 of 3×10^{-4} atm. The low concentration is expected in a saturated $CaSO_4$ solution. The experimental SO_4^{2-} concentrations in the 0-200 cm soil layer were lower (except one point) than the concentration predicted in saturated $CaSO_4$ solution (Fig. 1D). The concentrations in the 200-250 cm soil layer in high yield (N3) treatments were governed by $CaSO_4$ solubility in the presence of calcite. In low-yield treatments, the large L leached the sulfate below a depth of 250 cm. In the 250-450 cm soil layer, the SO_4^{-2} concentration in N3 treatments was supersaturated with respect to gypsum solubility in the presence of calcite (Fig. 1D), probably due to slow crystallization kinetics in these treatments. Sodium (Na) application in water and fertilizers was identical in all treatments, while M and R added Na to the soil. Overall, the water soluble Na profile (Fig. 1F) was quite similar in all the reported treatments, with largest peaks occurring in treatments RN3 and M2N0. Except at soil depth

>300 cm, the experimental sodium adsorption ratio [SAR, $C_{Na}/(C_{Ca}+C_{Mg})^{1/2}$, C in mM] fluctuated around the SAR of the irrigation water (3.1 $mM^{1/2}$) (data not presented). The soil pH profiles (Fig. 1G) were quite uniform with depth with small differences among treatments. Exceptions were treatments RN3 and M2N0 that had lower pH below 100 cm (~7.3 vs. all treatments mean of 7.8) and treatment M2N3 that had pH ~8 below 100 cm. The high pH in treatment M2N3 is compatible with the much lower Ca concentration in the soil water extract along the entire soil profile than in treatments M0N3 and RN3 (Fig. 1E). As a result of the lower Ca concentration in treatment M2N3, its SO_4 concentration was much higher than in the other two treatments (Fig. 1D).

Estimated water head available for leaching and leaching depth
The cumulative and year-specific water head available for solute leaching (L) were calculated according to Equation [3]. Representative annual results and the cumulative (35-year) L are summarized in Table 3. In the low-yield treatment M0N0 the cumulative L (1,368 cm) was ~60% higher than in treatment M2N3 that gave the maximum yield, compatible with the empirical Cl- profiles in soil in these treatments (Fig. 2). Differences in L among other treatments were also clear, but they were smaller than in the above mentioned treatments.

The solutes leaching depth (h, cm) was estimated from the cumulative L by Equation [5] above, assuming that salts displacement is instantaneous and driven by piston flow. The obtained leaching depth varied between 66 m in treatment M2N3 and 125 m in M0N0.

Under conditions of solute transport by mass flow only, $\theta = \theta_{fc}$, and soil hydraulic conductivity $K_{fc} = 0.003$ cm h^{-1}, the solute velocity v (K_{fc} / θ_{fc}) is 110 cm y^{-1}. Movement by diffusion at θ_{fc} is estimated to be ~10 cm y^{-1} which gives a total v of 120 cm y^{-1}. For $\theta_{fc} = 0.26$, the calculated v is ~200 cm y^{-1}.

Total (Kjeldhal) N concentration in soil (0-20 cm) as function of time
The amount of organic N added to soil in the manure treatments, and total (Kjeldhal) N found in the top 0-20 cm soil layer, both as function of time (1963-1994), are presented for four representative treatments in Fig. 2. During the first 14 years, between 1963 and 1976, the total (Kjeldhal) N concentration in soil increased in all treatments, including M0N0 and M0N3 that did not receive manure. The average accumulation rate (0-20 cm soil layer) in treatments M2N3, M1N1 and M0N0 during this period was 26.1, 16.1 and 3.1 mg N kg^{-1} soil y^{-1}, respectively. The average organic N supply rate in treatments M2N3 and M1N1 was 130 and 50 mg N kg^{-1} soil y^{-1}.

Table 3. The water head available for solute leaching (L) in representative crops and the cumulative L over the entire (35-years) experiment.

Year	Crop	Treatment					
		M0N0	M0N3	M2N0	M2N3	M1N3	RN3
		--------------------------------L (mm)[1]--------------------------------					
1974	Potato	364	225	320	300	308	292
1978	Sweet corn	702	494	492	457	497	489
1981	Processing tomato	687	711	526	526	606	606
1987	Muskmelon	464	304	298	194	233	103
1994	Carrot	469	415	418	388	444	379
		-------------------------Cumulative L (m)-------------------------					
1961-1994	All crops	13.68	8.47	9.60	7.28	8.31	7.88

Note: [1] L was calculated according to Equation [3].

A The permanent plots experiment (0-20 cm)

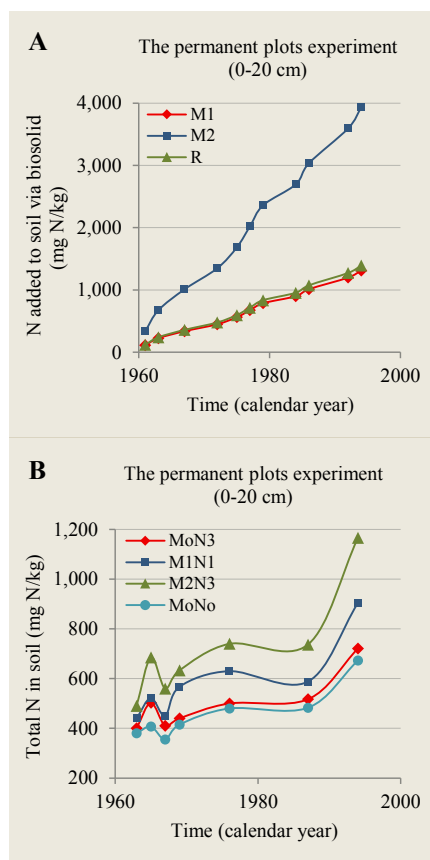**B** The permanent plots experiment (0-20 cm)

Fig. 2. Added organic N in applied manure (A) and organic (Kjeldhal) N (B) found in soil (0-20 cm) as a function of time in selected treatments.

The fraction of the added organic-N in treatment M2N3 that was recovered in the 0-20 cm soil test at the end of the experiment is calculated as [(soil organic N)$_{M2N3}$ - (soil organic N)$_{M0N0}$] / (organic N applied)$_{M2N3}$, all in units of [mg N kg^{-1} soil]. The recovered manure-N for treatment M2N3 over the period 1963-1976 is 18%, meaning that ~82% of the added manure-N was mineralized or moved by tilling to deeper soil layers. The recovered organic-N in treatment M1N1 was found to be 26%. Between 1976 and 1987, total N in soil in all treatments was steady (Fig. 2B) even though the supply of organic-N continued. In 1994, the concentration of total N in soil was much higher than in 1987 in all treatments. Repeating the recovered organic-N calculation for the 1987-1994 time interval gives % recovery of 28% and 30% for treatments M2N3 and M1N1, respectively.

Nitrogen supply vs. uptake

The difference between the quantity of mineral-N added to soil (fertilization + mineralization (NAD)) and N uptake (NUP) by plants (NAD-NUP) is part of the mass balance (Equation [4]), but it is worthwhile discussing it separately because it yields the treatments effect on crop N uptake efficiency. In treatment M0N3, the 35-year cumulative NAD-NUP was 542 g N m^{-2} (Table 4). When the N3 level was supplemented by manure at level M1 (M1N3), or by city refuse compost (RN3) the cumulative NAD-NUP increased to 600 g N m^{-2}. Treatment M2N0 gave interesting results: its 35-years cumulative dry matter was 19.4 kg m^{-2}, which is close to the 25.2 kg m^{-2} obtained in treatment M2N3 (Table 2); the difference in fresh edible yield between those treatments was even smaller (Table 2). Despite the small difference in yield, the cumulative NAD-NUP in treatment M2N0 was 65 g N m^{-2} and in treatment M2N3 665 g N m^{-2} (Table 4). In treatment M0N0, the cumulative NAD-NUP was ~0, indicating that the original assumption of 1.5% soil organic-N mineralization per year (footnote Table 1) is reasonable.

The NUP:NAD ratio is the crop N uptake efficiency. In treatment M0N0 the cumulative uptake was 140 g N m^{-2} (see later in Table 6) and since no N was added, it indicates the long-term soil mineralization power (~4 g N m^{-2} y^{-1}). In treatment M0N3 the cumulative NUP was 406 g m^{-2} and NUP:NAD = 0.51. This ratio is the N uptake efficiency when N was supplied solely as fertilizer. In treatment M2N0 (all N supplied as manure) the NUP was 343 g N m^{-2} and NUP:NAD 0.45. Combining M2 and N3 (treatment M2N3) gave cumulative NU of 523 g N m^{-2} but reduced the N uptake efficiency to 0.34.

In a few cases in Table 4 negative values were obtained, meaning greater mineral-N supply by the soil than predicted. This could stem from the fact that mineralization took place below the 0-40 cm soil layer as well. It is noted that the experimental NUP values (see later in Table 6) in treatments with high yield were in line with data on optimal nutrient uptake by field crops in Israel published by Bar-Yosef (1999).

Mineral and organic-N in the root zone along the experiment

Mineral N in soil was determined to a depth of 120 cm four times during the experiment (Table 5). The quantity found was proportional to fertilizer and manure application rates. The mineral N did not accumulate in soil because, in all cases, the water head available for leaching (L) was sufficiently large to leach nitrate beyond the depth of 120 cm. The 35-year average mineral-N quantities in soil in

Table 4. The difference between mineral-N added[+] to soil (NAD) and N uptake (NUP) by representative crops and years, and cumulative differences over the entire (35-years) experiment period.

Year	Crop	Treatment					
		M0N0	M0N3	M2N0	M2N3	M1N3	RN3
		----------------------NAD-NUP *(g N m^{-2})*----------------------------					
1974	Potato	0.2	20.6	5.6	14.4	11.4	9.6
1978	Sweet corn	1.8	27.0	7.8	36.9	29.2	30.9
1981	Processing tomato	-6.2	9.3	-9.4	5.1	8.0	8.2
1987	Muskmelon	0.0	22.5	3.9	25.4	23.9	21.4
1994	Carrot	-8.0	14.3	-7.3	19.5	16.4	12.6
1961-1994	All crops	12	542	65	665	605	599

Note: [+]NAD = Fertilizer N + Manure mineralized N + Soil organic matter mineralized N. Mineralization was calculated according to Equation [2].

Table 5. Seasonal variations in N quantities (mineral and organic) in soil. Values in parenthesis were predicted according to Equation [2][1].

Year[2]	Crop	Treatment					
		M0N0	M0N3	M2N0	M2N3	M1N3	RN3
		------------- *Mineral-N (g m⁻², 0-120 cm)[3]*------------------					
1969	Processing tomato	12	22	26	28	25	22
1974	Potato	16	18	24	42	36	38
1978	Sweet corn	17	39	31	51	46	55
1994	Carrot	12	13	35	42	40	35
1961-1994	Mean	14+3	22+7	26+7	36+8	33+9	31+10
		-----------------*Organic-N (g N m⁻², 0-40 cm)[4]*-----------------					
1963	Potato	230	250	300	300	240	300
		(280)	(274)	(330)	(321)	(358)	(334)
1967	Cotton	215	245	300	335	280	310
		(248)	(250)	(348)	(341)	(338)	(338)
1969	Processing tomato	240	250	335	360	340	340
1976	Pepper	270	280	340	445	385	310
		(205)	(222)	(350)	(318)	(337)	(340)
1987	Muskmelon	290	310	470	442	400	400
		(166)	(180)	(485)	(462)	(328)	(361)

Note: [1]The reference year for predicting organic-N in soil was 1969. [2]Since 1986, the plots were irrigated by trickle irrigation and N was applied as NH_4NO_3 via the water. [3]Mineral-N = NH_4 + NO_3; NH_4-N comprised ~10% of mineral-N. [4]Organic-N concentration in soil (0-40 cm) at the beginning of the experiment was 200 g N m⁻².

treatments M0N0 and M2N0 were 14 and 26 g N m⁻², while in treatments M0N3 and M2N3 the quantities were 22 and 36 g N m⁻², respectively (Table 5).

Organic-N was measured in the 0-40 cm soil layer five times (Table 5), showing increase in quantity between 1963 and 1987: in manured plots, it increased from ~300 to ~430 g organic-N m⁻², while in M0 treatments it was only ~250 to ~300 g m⁻². The fluctuations with time are explained by the fact that manure was applied every 3-to-5 years, and soil samples were taken regardless of the time after manure application. The experimental organic-N results in Table 5 were accompanied by the mineralization model predicted values (Equation [2]). The model predicted a decrease in soil organic-N (SON+MON) with time in treatment M0, negligible variation with time in treatments M1 and R, and increase with time in treatment M2 (Table 5). The experimental soil organic-N, however, increased in all treatments, including M0. The main reason for discrepancies between experimental and predicted

results was the larger quantity of plant residue incorporated into the soil than assumed in the model. In treatment M2, the contribution of incorporated plant residue was small relative to manure application therefore the agreement between experimental and predicted data was better than in other treatments.

Ions mass balance in soil
The inorganic ions mass balance in soil after 35-year of experiment is presented in Table 6. The only term in the mass balance Equation [4] that was not determined experimentally is the N leaching below 420 cm (IL). The IS data at the end of the experiment is known from the soil sampling to the depth of 420 cm (Fig. 1) coupled with the assumption that the initial amount in soil ($IS_{initial}$) is negligible relative to added quantities. The calculated IL in treatment M2N3 was 557 g N m⁻². In treatments RN3 and M1N3, leaching was 430-to-557 g N m⁻² as compared with only 85-to-176 g N m⁻² found in the soil at the end of the experiment. In treatments M2N3 and RN3 N leaching was greater than in treatments

M0N3 and M1N3 (535 vs. 430 g N m⁻²) due to the greater mineralization. In treatment M0N0 and M2N0, no nitrate was leached below 420 cm and the balance was negative, indicating that in these treatments neglecting $IS_{initial}$ was unjustified.

The Cl⁻ leaching beyond 420 cm in the various treatments ranged between 4,135 g m⁻² (M2N0) and 3,410 g m⁻² (M0N3) (Table 6). The leaching increased with added manure due to Cl⁻ presence. The expected impact of transpiration on Cl⁻ leaching was probably expressed below a depth of 420 cm, as was found in deep soil sampling in the Permanent Plots Experiment at Bet Dagan (Feigin and Halevy, 1995).

Sulfate did not leach beyond 420 cm and the added amounts (as superphosphate and ammonium sulfate, and in manure) accumulated in the 0-420 cm soil layer (Table 6), which is compatible with the sulfate concentration profiles in soil shown in Fig. 1D. The quantity of sulfate in the 0-420 cm soil layer exceeded the difference between application and uptake (Table 6), thus indicating that the assumption of negligible sulfate $IS_{initial}$ was incorrect.

Potassium, sodium and phosphate status in soil
Potassium uptake by plants in treatments M0, M1 and R exceeded its addition to the soil (Table 6). Exchangeable and fixed K contributed to the unaccounted-for K. In treatments M2N0 and M2N3, surplus K (355 and 74 g K m⁻², respectively) should be found in the soil as K addition exceeded uptake and K mobility in Gilat soil is limited. The soil-K harvesting observed in treatments M0, M1 and R indicates that in order to sustain the soil fertility, K in fields well fertilized by N and P must be added to replace at least the K consumption by the crop.

Sodium accumulation in soil was unaffected by treatments as it was added

Table 6. Inorganic ions balance in soil after thirty-five years of experiment.

Element	Treatment					
	M0N0	M0N3	M2N0	M2N3	M1N3	RN3
---------------------------------*Application (g element m^{-2})[1]*---------------------------------						
N	152	948	407	1,188	1,070	1,081
K	237	237	957	957	477	477
Cl	4,212	4,212	4,692	4,692	4,372	4,372
S	434	1,090	434	1,090	1,090	1,090
Na	2,589	2,589	2,784	2,784	2,654	2,654
------------------------------------*Uptake (g element m^{-2})[2]*------------------------------------						
N	140	406	343	523	464	482
K	316	693	602	883	680	790
Cl	48	108	97	126	115	118
S	48	108	97	126	115	118
Na	10	21	19	25	23	24
--------------------------*Application minus uptake (g element m^{-2})*--------------------------						
K	-79	-456	355	74	-203	-313
Na	2,579	2,567	2,765	2,759	2,631	2,630
----------*Quantity in soil (0-420 cm) at the end of experiment (g element m^{-2})*----------						
Min-N	136	105	66	108	176	85
Cl	482	694	460	469	590	490
S	456	1,995	468	1,234	1,889	1,825
--------------*Quantity leached beyond a depth of 420 cm (g element m^{-2})*--------------						
Min-N	-124	437	-2	557	430	514
Cl	3,682	3,410	4,135	4,097	3,667	3,764
S	-70	-1,013	-131	-270	-914	-853

Note: [1]Application includes fertilizer + manure + water. [2]N, P, K uptake according to plant analyses; other elements according to dry matter multiplied by approximate concentrations in plant (Cl, S 0.5%, Na 0.1%).

mainly via the irrigation water with negligible contribution by added manures (Table 6), and its uptake by plants is negligible in comparison with its addition to soil.

Phosphorus addition to the soil exceeded its consumption by plants over the 35 years by a margin of 80-to-225 g P m^{-2}, depending on manure treatment (data not presented). The excess P was retained in soil by adsorption, fixation, precipitation and biological reactions.

Phosphorus and K fertilizers were applied at identical rates to all treatments, but the manure treatments created differential P and K availability levels in soil. The availability of both P and K was evaluated by a single NaHCO$_3$ extract, as suggested by Bar-Yosef and Akiri (1978), except in 1963 when K was evaluated by the CaCl$_2$ 0.01M (1:7) extract (Table 7). The impact of N fertilization level on P and K availability in soil at any manure level was small, with a trend of decrease in available P and K concentration in soil at the N level that resulted in maximum crop yield.

Table 7. Available P and K in soil as function of treatment and time.[1]

Treatment	NaHCO$_3$ extractable P						NaHCO$_3$ extractable K			CaCl$_2$
	0-20 cm					20-40 cm	0-20 cm		20-40 cm	0-20 cm
	1963	1965	1987	1991	1994	1991	1991	1994	1991	1963
	------------------------------------*mg P kg soil^{-1}*------------------------------------						--------------*mg K kg soil^{-1}*---------------			*mg K L^{-1}*
M0N0	-	-	23	28	33	19	255	462	192	-
M0N3	-	-	21	27	31	16	275	433	170	-
M2N0	-	-	41	67	120	42	405	690	345	-
M2N3	-	-	39	62	111	33	424	800	266	-
M1N3	-	-	34	42	62	35	386	583	250	-
RN3	-	-	26	32	41	24	266	540	213	-
---*Main factor means*---										
N0	25	49	31	45	63	30	320	543	176	23
N1	24	44	33	38	69	24	300	621	244	25
N2	24	40	30	42	69	27	300	578	318	27
N3	21	40	30	41	62	27	337	589	204	24
M0	14	20	25	29	35	18	258	458	248	21
M1	25	41	33	42	63	28	333	569	225	27
M2	37	88	39	64	122	37	408	818	232	29
R	18	24	27	37	41	25	263	486	237	22

Note: [1]In 1963 and 1965 only the mean P and K values were available. Manure doses per application in treatments M0, M1, M2 and R were 0, 30, 90 and 30 t ha^{-1}, respectively. The manure was added in the years 1961, 1963, 1967, 1972, 1976, 1978, 1979, 1984, 1986, 1992 and 1994.
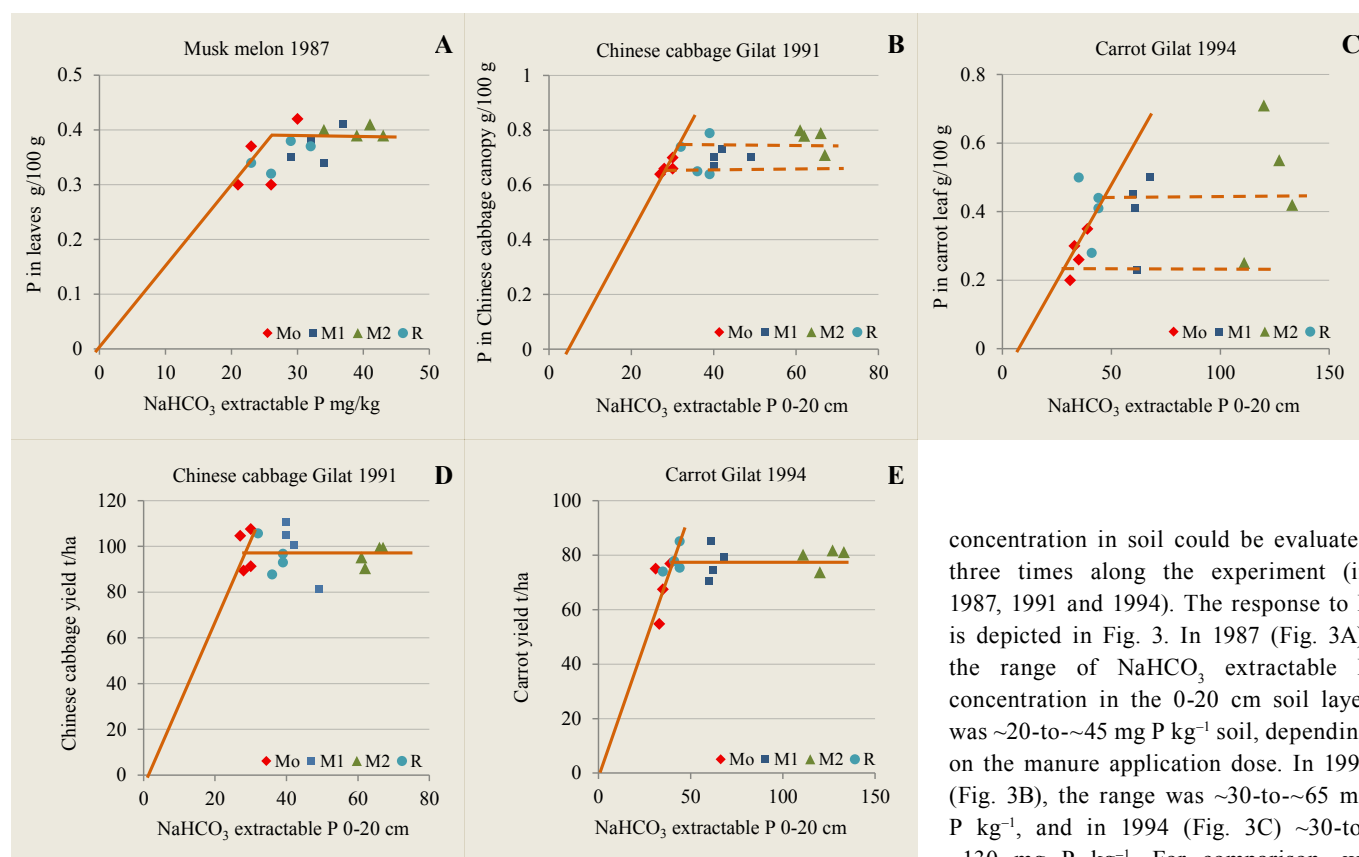
Fig. 3. Percentage of P in leaves in muskmelon (A), Chinese cabbage (B) and carrot (C), and yield response to available P in soil of Chinese cabbage (D) and carrot (E).

The time effect on P availability in soil (0-20 cm) can be best evaluated via the manure mean fertilizer treatments (Table 7). Treatment M0 received no manure, but the $NaHCO_3$ extractable P concentration in soil increased from 14 mg P kg^{-1} in 1963 to 35 mg P kg^{-1} in 1994. The source of this P is fixed P and sparingly soluble P compounds that were mobilized by root activity, and by mineralization of soil organic-P.

Treatments M1, M2 and R (Table 7) clearly increased the available P concentration in soil between 1963 and 1965, but in 1987 the concentrations declined and were lower than in 1965 and even closer to the concentrations that prevailed in 1963. This was the result of fewer manure applications between 1979 and 1987 than prior to 1979. In 1991, the available P concentration

regained the values that existed in 1965, and in 1994 the concentration steeply increased thanks to manure application in 1992. The results show that there is only a short-term impact of manure on available P in soil, and 3-4 years with no manure supply results in re-equilibration of P in soil depending on soil pH and Ca^{2+} activity.

The available P and K concentrations in soil increased in the order M2 > M1 > R > M0. That was also the order in the case of $CaCl_2$ soluble K (1963). In 1991, available P and K were determined in both the 0-20 and 20-40 cm soil layers. The concentration in the deeper soil layer varied between ~50 and ~75% of that in the top soil layer.

The crop response to available P and K

concentration in soil could be evaluated three times along the experiment (in 1987, 1991 and 1994). The response to P is depicted in Fig. 3. In 1987 (Fig. 3A), the range of $NaHCO_3$ extractable P concentration in the 0-20 cm soil layer was ~20-to-~45 mg P kg^{-1} soil, depending on the manure application dose. In 1991 (Fig. 3B), the range was ~30-to-~65 mg P kg^{-1}, and in 1994 (Fig. 3C) ~30-to-~130 mg P kg^{-1}. For comparison, we can estimate the theoretical maximum increase in soil P concentration due to application of 30 t manure ha^{-1}, which is the dose per application in treatment M1. In the dairy manure (~50% water and 0.6% P in dry matter), this dose elevated the P concentration by ~35 mg P kg^{-1} soil (0-20 cm soil layer). Two manure applications between 1991 and 1994 can explain the observed increase in available P concentration in this treatment (from ~38 mg P kg^{-1} in 1991 to ~70 in 1994 and bearing in mind that the $NaHCO_3$ extract does not release the entire adsorbed P in the soil). The effect of N at each manure level on available P concentration was significant in 1987 and negligible later on. Despite the difference in tissue P concentration between the three crops, the threshold $NaHCO_3$-P concentration above which no increase in tissue P was obtained was 25-30 mg P kg^{-1} soil (Figs. 3A, 3B, 3C). This was also the threshold in the relationship between crop edible yield and available P concentration
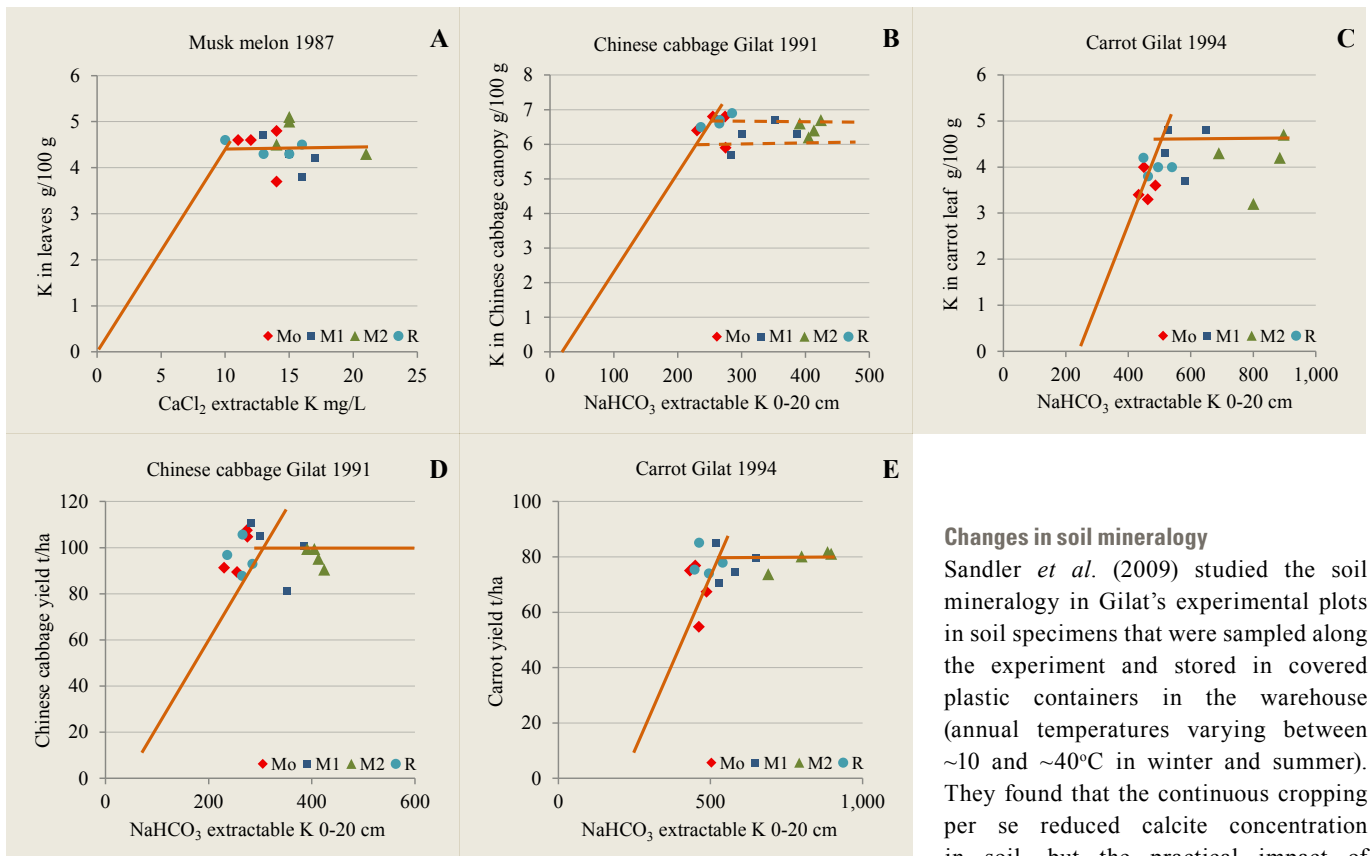
Fig. 4. Crop yield, percentage of K in leaves of muskmelon (A), Chinese cabbage (B), and carrot (C), and yield response of to available K in soil of Chinese cabbage (D), and carrot (E). The response in %K in leaves in 1987 is to $CaCl_2$ soluble K.

in the soil (Figs. 3D, 3E). The straight lines to the abscissa show the crop response to soil available P when it is the main growth limiting factor in the system.

The crop response to soil available K is presented in Fig. 4. In 1987 (muskmelon), the threshold concentration of $CaCl_2$ soluble K was 8 mg K L^{-1} (Fig. 4A), and this value was exceeded even in the un-manured treatment M0. The available K concentration in soil in 1991 and 1994 was evaluated by the $NaHCO_3$ 0.5M extract that was used to estimate available P in soil (Bar-Yosef and Akiri, 1978). The obtained concentrations spread in 1991 was between ~220 and ~420 mg K kg^{-1} soil, the values increasing with increasing manure application rates (Fig. 4B). In 1994, the spread was ~410-to-

~900 mg K kg^{-1} soil (Fig. 4C). To assess this increase, the K found in 30 tons of dairy manure and mixed in the 0-20 cm soil layer of 1 ha (treatment M1) can increase the soil K concentration by up to 150 mg K kg^{-1}. It is interesting to note that in treatment M0, in which K uptake exceeded fertilizer-K application and organic matter has not been added, the soil K concentration still increased with time. A reasonable explanation is that fixed K was released to the soil solution in response to the depletion of K by the plants. In Chinese cabbage (1991), the threshold $NaHCO_3$-K concentration in both yield and % K in leaves was ~200 mg K kg^{-1}, while in carrot (1994) it was ~500 mg K kg^{-1} (~1.2 mmol(c) 100 g^{-1} soil) (Figs. 4D, 4E).

Changes in soil mineralogy

Sandler *et al*. (2009) studied the soil mineralogy in Gilat's experimental plots in soil specimens that were sampled along the experiment and stored in covered plastic containers in the warehouse (annual temperatures varying between ~10 and ~40ºC in winter and summer). They found that the continuous cropping per se reduced calcite concentration in soil, but the practical impact of this finding was small. The long-term fertilization had a slight impact on the soil's mineralogical composition: high manure and fertilization rates caused a small decline in soil illite due to K consumption by plants and a subsequent increase in soil smectite.

Conclusions

The main conclusions from the Gilat LTFE can be summarized as follows:

1. Replacing fertilizer-N by manure-N under controlled irrigation and sufficient N supply had long-term beneficial effect on reducing underground water pollution, and minor adverse effect on crop yield.

2. Enhanced dry matter (DM) production due to fertilization reduced nitrate and chloride leaching depth, thus supporting the theory that transpiration is directly proportional

to DM production. Applying this theory allowed estimating the cumulative (35-year) water head available for leaching (L), which varied between 730 cm in treatment M2N3 and 1370 cm in treatment M0N0. Assuming piston solute flow, these L values could displace soluble salts to depth of 66 m in treatment M2N3 and 125 m in M0N0 at estimated velocity of ~120 cm y^{-1}.

3. In the ample N supply treatment (M2N3), which represents conditions of high NO_3^- pollution hazard, the estimated cumulative (35-year) NO_3^- leaching was 557 g N m^{-2} and the corresponding Cl$^-$ leaching was 4,097 g Cl m^{-2}. In treatment M2N0 the corresponding leaching values were 0 and 4,135 g m^{-2}.

4. The [cumulative irrigation] - [cumulative estimated crop transpiration] varied between 60 cm (treatment M2N3) and 700 cm (M0N0). This indicates that irrigation in high yield treatments was efficient, and deep leaching was done by winter rain.

5. The long-term soil cultivation had a negligible effect on the crops response to N fertilization treatments.

6. The long-term N uptake efficiency was 0.51 in treatments receiving all the N as mineral-N and 0.45 in treatments receiving all the N as organic-N.

7. High manure and fertilizer application rates caused a small decline in soil illite due to K consumption by plants and a subsequent increase in soil smectite.

8. The soil organic-N (SON) increased with time in all treatments depending on the organic-N application level. In treatment M2 the increase in the 0-40 cm soil layer was from 280 (in
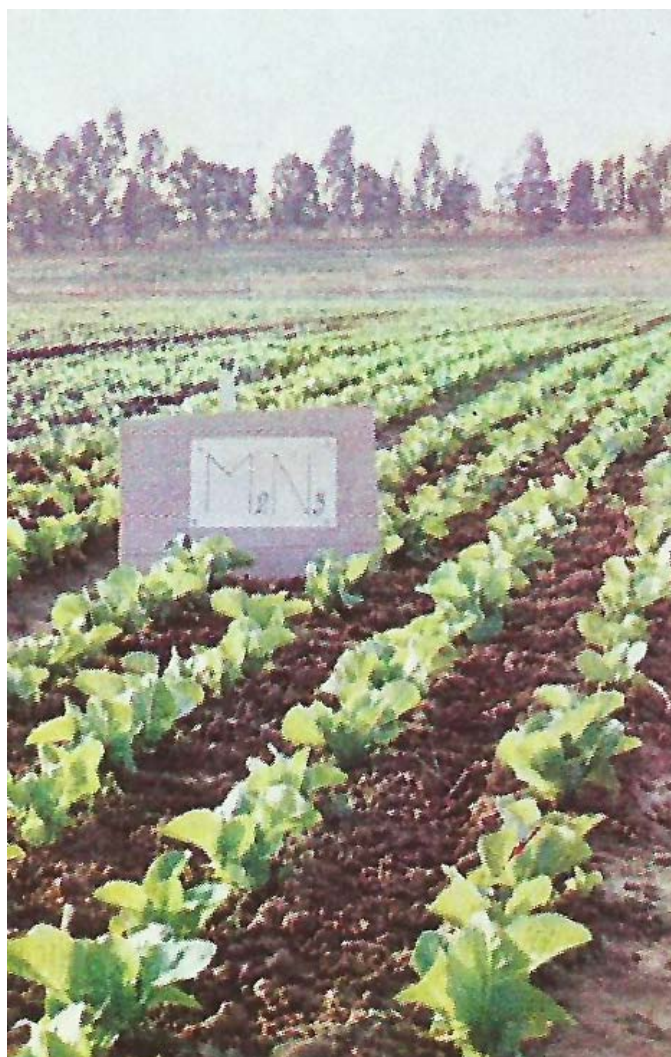

Photo 1. Authentic picture of the lettuce crop in the Gilat LTFE, 1970. The plots were 16 m long and 6 m wide (3 beds per plot). Photo by author.

Photos 2. Overview of the Gilat LTFE in 1976 (left) and 1981 (right). The soil color is misleading, not reflecting the natural color of the experimental loess soil. Photos by author.

1963) to 470 g N m^{-2} (in 1987), while in M0 the increase was from 280 to 300 g N m^{-2}. The mineralization rate of SON was 4 g N m^{-2} y^{-1}.

9. Potassium uptake, under recommended K fertilization and low manure application, exceeded the K addition to soil and caused depletion of soil K. The threshold soil CaCl$_2$ soluble K, above which no muskmelon yield increase was obtained, was 8 mg K L^{-1}. The corresponding threshold NaHCO$_3$ extractable K in soil was 220 mg K kg^{-1} in Chinese cabbage and 450 mg K kg^{-1} in carrot.

10. An observed beneficial effect of manure addition on available P in soil was short-termed, and 3-4 years without re-supply of manure resulted in re-equilibration of mineral-P in soil depending on soil pH and Ca^{2+} activity. The threshold NaHCO$_3$ extractable P in soil above which no increase in tissue P concentration or crop edible yield were obtained was 25-30 mg P kg^{-1} soil.

11. Available P and K concentration in soil in the 20-40 cm layer varied between ~50 and 75% of that in the 0-20 cm soil layer.

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The paper "Conclusions from the Permanent Plot Experiment at Gilat, Israel: Long-Term (35-Year) Effects of Manure and Fertilizer on Crop Yield, Soil Fertility, N Uptake, and Solutes Leaching in Soil" also appears on the IPI website at:

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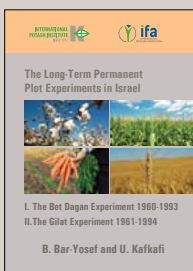
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