EFFECTS OF CITRUS AGRICULTURE ON RIDGE LAKES IN CENTRAL FLORIDA

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Abstract. The U.S. EPA sampled 149 lakes in Florida as part of the Eastern Lake Survey. The majority of peninsular survey lakes lying south of 29° latitude have been chemically altered by livestock operations, residential development, and especially citrus agriculture. The numerous doline lakes in citrus belts are highly enriched in K, Na, Mg, Ca, Cl, and SO_4 because of specific grove practices; here Gran alkalinities are moderately elevated above non-cultural 'background' because of liming with dolomite. Seepage lakes in citrus districts also reveal pronounced but erratic enrichment in nitrate, but not P. In Highlands County their trophic state is determined by P and is thus indistinguishable from hydraulically and morphometrically similar lakes lacking cultural influences. Chemical tracers of cultural origin can be used to help resolve the hydraulic properties of regional seepage lakes, and might find application in diagnosing best management practices in their terrestrial catchments.

1. Introduction

As part of the Eastern Lake Survey (ELS) the U.S. Environmental Protection Agency (EPA) sampled 149 lakes in Florida during December 1984. Linthurst *et al.* (1986) and Eilers *et al.* (1988) explained the rationale behind this important survey, summarized the regional findings, and attempted a preliminary synthesis and overall evaluation of the study.

The Florida lakes exhibited many unique and/or enigmatic relationships among the solutes (Linthurst *et al.*, 1986), including: (1) a poor correlation between Na and Cl; (2) a poor correlation between Cl concentration and proximity to the coast; (3) a poor and counter-intuitive correlation between sulfate and alkalinity; (4) a poor correlation between the sum of divalent base cations (Ca, Mg) and Gran alkalinity = acid neutralizing capacity (ANC); (5) an unusual stoichiometry between Ca and Mg. These paradoxical relationships among major ions must be explained if we are to gain an adequate understanding of the hydrologic characteristics of Florida lakes, and resolve their sensitivity to acidic deposition and anthropogenic disturbances of their terrestrial catchments. Using primary data from the ELS (Kanciruk *et al.*, 1986), I examine how development has influenced the chemistry and trophic state of lakes in ridge sections of central Florida.

2. Methods

2.1. GEOGRAPHIC OVERVIEW AND SET PARTITION

Linthurst *et al.* (1986) described the criteria for lake selection, the sampling protocols,

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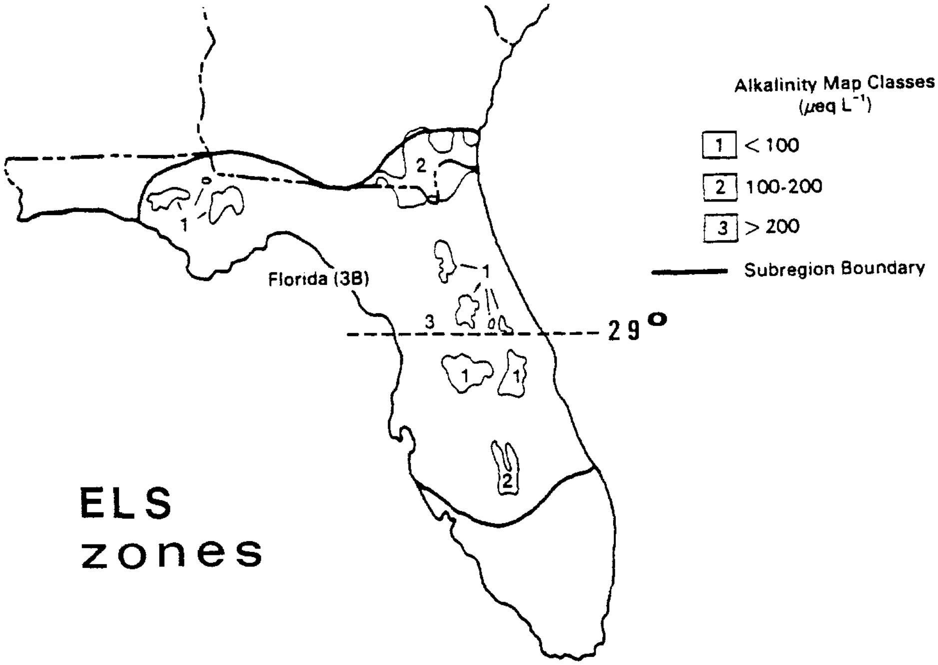


Fig. 1. Florida lake regions sampled during the Eastern Lake Survey. ELS-3B1 lakes from south of 29° latitude are in the 'central' citrus district. The southern section of ELS-3B2 is set in Highlands County, in the southern Lake Wales Ridge Province.

and the analytical procedures used during the ELS. The Florida section of the ELS included 36 'regular' (probability sample) lakes in zone 3B3, the subclass richest in ANC. These sites were widely dispersed, and included typical hardwater lakes from the Gulf Coastal Lowland (Figure 1). The less well buffered ELS-3B1 and 3B2 sites from the peninsula (Figure 1) consisted mainly of doline lakes (Hutchinson, 1957) perched above the Floridan aquifer in excessively-drained Astatula fine sands developed on relic beach terraces (Conover *et al.*, 1984).

On account of their good drainage and relative resistance to frost, ridges south of 29° latitude are well suited to citrus, but only after being adequately fertilized. Because of the relationship between latitude and frost severity, this parallel ca. 50 km north of Orlando (Figure 1) demarcates the limit of commercial cultivation of citrus on highlands of the Florida peninsula preceding the devastating freezes of winter 1983–84 (Ziegler and Wolfe, 1975).

In light of the above, I partitioned the ELS data geographically (N or S of 29° latitude) and focused my analysis on the 76 ELS-3B1 and 3B2 lakes lying in the southern sector (this enumeration includes 3B1–29, but excludes 3B1–61, both near 29°). The native ridge soils in Florida have low cation exchange capacities and low base saturation levels (Pollman and Canfield, 1991), and are acutely deficient in K (Ziegler and Wolfe, 1975). Thus, a lake's K concentration might serve as a sensitive and convenient indicator of watershed modification (Morgan and Good, 1988). Potassium is then linked to other cultural solutes because successful cultivation of citrus on Florida's sandy ridge soils requires an integrated management plan (Section 3.3). These hypothesized linkages among geography, land use, and biogeochemistry were checked using map (USGS 1:100 000 metric; 1978–1981) and field (March, November 1987) reconnaissance. Here special attention was paid to chemical outliers.

2.2. DATA ANALYSIS

For each solute X I define the non-marine 'excess concentration' by

$$X^{*} = X - r_{X:\mathrm{Na}}\mathrm{Na}, \tag{1}$$

where X and Na are the reported (Kanciruk *et al.*, 1986) lake concentrations of X and Na (by equivalents), and $r_{X:\mathrm{Na}}$ is the X:Na ratio in seawater. For lakes with low K this formulation is essentially equivalent to the more conventional one based on Cl (see below). For lakes with high K Equation (1) avoids the probable bias stemming from watershed fertilization with KCl, the most important commercial potash mineral (Table I). Equation (1) is insensitive to lake-specific differences in the evapo-concentration factor (ECF), and to pumping of irrigation water from the upper Floridan aquifer (Section 3.2.).

I also define

$$X^{**} = X - r_{X:\mathrm{Na}}\hat{\mathrm{Na}}_{bg}, \tag{2}$$

where $\hat{\mathrm{Na}}_{bg}$ represents the mean 'background' Na concentration (157 meq m^{-3}) in the 4 Highlands County lakes with minimum K. Unlike Equation (1), Equation (2) is sensitive to lake-specific differences in ECF. However, it avoids the probable bias introduced into Equation (1) by the significant commercial use of Na-bearing fertilizers in Florida (Table I).

Multivariate regression was used for analyzing the statistical relationships among solutes. Most of these regressions involve K as an independent variable because K is the base cation with the lowest non-cultural 'background' concentration for all natural waters in Florida. Residuals were studied, and where indicated, regressions rerun to test for the importance of sensitive outliers. These outliers were also checked

TABLE I

Potassium content (as K_2O, t) of direct application fertilizers consumed in Florida during year ended June 30 (U.S. Dept. Agric., annual)

Year	KCl	(K–Mg)SO_4	KNO_3	(K–Na)NO_3	K_2SO_4	Organics	Other
1982	11,795	1,198	2,498	5,817	595	644	3,545
1983	13,142	1,014	1,775	6,717	569	807	4,873
1985	10,396	2,648	1,589	5,021	716	957	4,613

TABLE II

Chemistry of 'citrus ponds' *vs* regional aquifer near Orlando, Florida

I.D.	A_0	z	SDT	Color	K	Na	Ca*	Mg*	ANC	SO_4	Cl*	Cl**	Na**	NO_3
(A) Seepage lakes with maximum K (ELS-3B1)														
007	6	2.4	0.7	45	639	518	1751	2330	1649	2478	458	878	361	36.0
068	11	6.7	1.4	40	578	615	1460	2071	1473	2228	372	943	458	0.0
059	16	5.8	1.7	20	538	324	1215	1630	1369	1522	748	906	167	27.0
(B) Floridan aquifer at Groveland, FL (Back and Hanshaw, 1970)														
Well	–	–	–	–	13	156	2093	307	2344	33	2	0	-1	1.5

*, ** See Equations (1) and (2) (text)

Lakes all near 28°29′ N; 81°35′ W, 25 km ESE of Groveland, FL.

Parameters: A_0 = lake area (ha); z = lake depth (m) at EPA sampling site; SDT = Secchi depth transparency (m); concentrations in meq m^{-3} except color (CPU).

against dominant land use classifications, as established by map and field reconnaissance. All concentrations are expressed here in meq m^{-3}, except for total phosphorus (P_t; mg m^{-3}), dissolved organic carbon (DOC; μM), and true color (CPU = chloroplatinate units).

3. Results and Discussion

3.1. OVERVIEW

As expected, there was a remarkable covariance between latitude (N or S of 29°), land use, and K concentration among the ELS lakes. Only one of 44 3B1 lakes from north of 29° had K>14 meq m^{-3} (Chipco), whereas only 6 of 76 3B1 and 3B2 lakes from south of 29° had K<18 meq m^{-3}. The three small ponds with maximum K (Table II) are clustered near 28°29′ N; 81°35′ W; and surrounded by commercial citrus groves. By contrast, the four Highlands County lakes with K<11.5 meq m^{-3} have watersheds that were largely covered by native scrub vegetation at the time of the ELS. The latter include Lake Annie (3B2–053), lying in the Archbold Preserve (Layne, 1979).

3.2. STATISTICAL RELATIONSHIPS AMONG MAJOR IONS

The statistical relationshops among major ions are summarized in this section; their

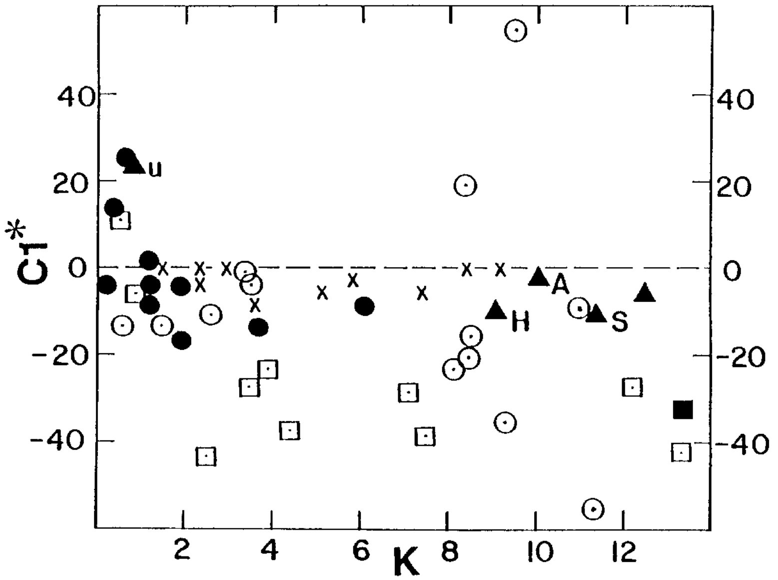


Fig. 2. Cl* *vs* K (both in meq m^{-3}) for ELS lakes (3B1 and 3B2) with K<15 meq m^{-3} (no samples in K range: 13.5 to 18.0). Symbols: X = NW panhandle; ● = Okeefenokee; ○ = Trail-Ridge-Interlachen; □ = Ocala NF-Weirsdale; ■ = Bullock Lake; ▲ = Highlands County (Lake Names: A = Annie, H = Hill, S. = Silver, u = unnamed).

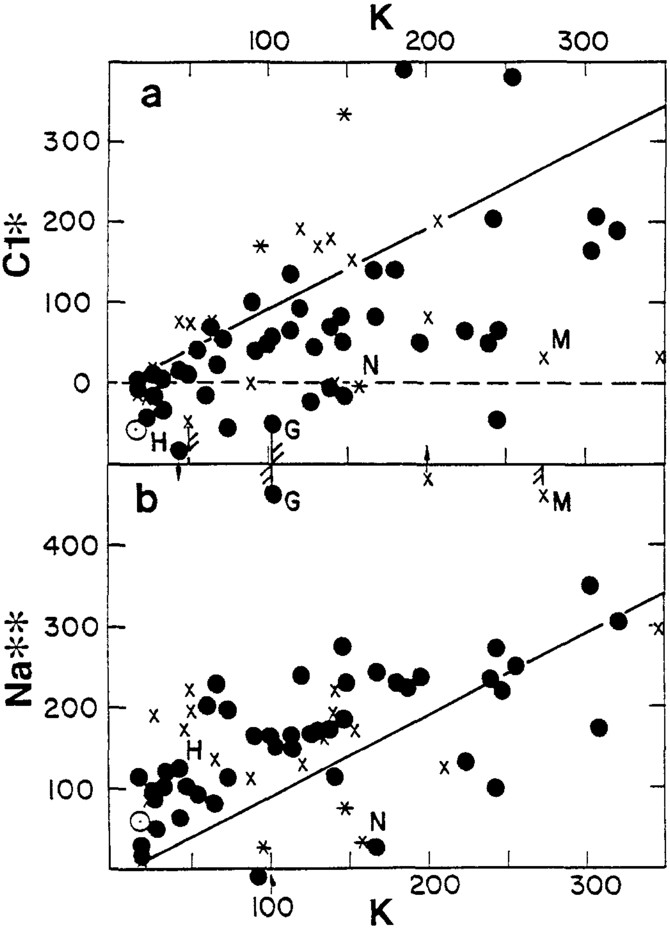
links to citrus agriculture are then developed in Section 3.3. The Florida lakes with low K do not have anomalous Cl concentrations or Na:Cl ratios. Here, CL* is either zero (marine balance) or slightly negative (small watershed Na source) (Figure 2). By contrast, Cl* increases with K for $K > 15$ meq^{-3}. Despite considerable scatter, most such points fall below the 1:1 line, and there is no discernible contrast ($p > 0.1$) between ELS-3B2 lakes in Highlands County *vs* ELS-3B1 lakes near Orlando (Figure 3a).

The Na** are also $\gg 0$ for lakes with $K > 15$ meq m^{-3}, but rarely exceed the 1:1 line except for $K < 150$ meq m^{-3} (Figure 3b). For the full set ($N = 76$):

$$\text{Na}^{**} = 103(18) + 0.55(0.10)\ \text{K}^{**} \qquad R^2 = 0.29, \tag{3a}$$

where the numbers in parentheses are standard errors. However, if urbanized Glenada (3B2-19) and two ponds near Umatilla (3B1-44, 45) are excluded:

$$\text{Na}^{**} = 93(12) + 0.50(0.06)\ \text{K}^{**} \qquad R^2 = 0.45. \tag{3b}$$



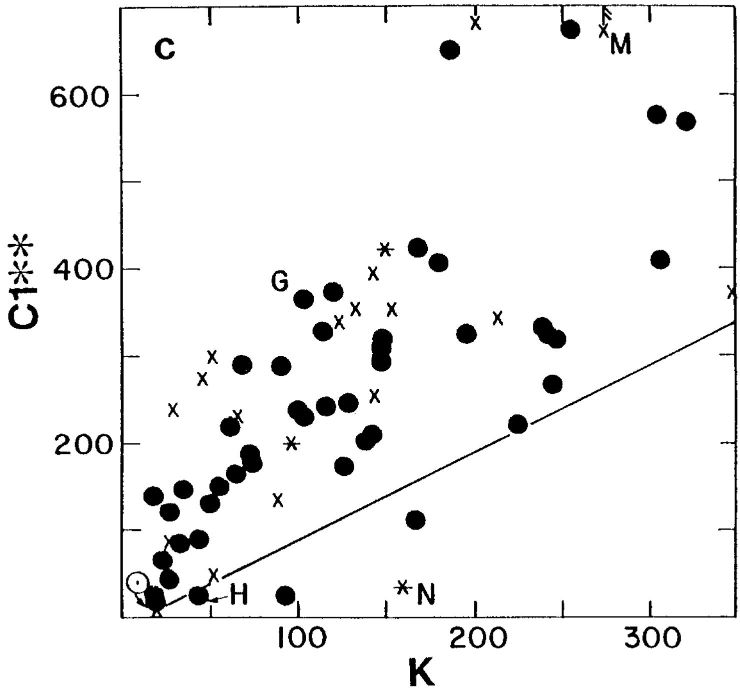


Fig. 3. (a) Cl* *vs* K (both in meq m^{-3}) for ELS lakes (3B1 and 3B2) with K > 18 meq m^{-3}. Symbols: o = Chipco (3B1–32); * = Weirsdale district; X = central Florida citrus belt (S of 29°); ● = Highlands County. Lake Names: G = Glenada (3B2–019), H = Hog (3B2–101), M = Mary (3B1–045), N = No Name (3B1–039). Glenada, Hog, and Mary are heavily urbanized; neither H nor N is influenced by citrus. Line of equal enrichment shown. (b) As for (a) but for Na**. Note that K** = K–3.5 meq m^{-3}. (c) As for (a) but for Cl**.

When a quadratic term is added, it is not significant (partial-t) = –1.55); nor is there a significant sub-regional contrast (see above).

Cl** increases more sharply and consistently with K than Na** (Figure 3c; Table II). Thus, the regression line is free of outliers ($N = 76$);

$$\text{Cl}^{**} = 87(19) + 1.44(0.11)\ \text{K}^{**} \qquad R^2 = 0.71. \tag{4}$$

Excluding Glenada and outlier 3B1–59:

$$\text{Cl}^{**} = 21(23) + 1.46(0.11)\ \text{Na}^{**} \qquad R^2 = 0.71. \tag{5}$$

However, the multivariate model:

$$\text{Cl}^{**} = 20(19) + 1.08(0.10)\ \text{K}^{**} + 0.64(0.10)\ \text{Na}^{**} \qquad R^2 = 0.82 \tag{6}$$

demonstrates that Cl enrichment depends on *both* K and Na.

Mg* and Ca* also increase rapidly with K, attaining values two orders of magnitude greater than found in acidic seepage lakes in North Florida (Figure 4; Table II). Even if two Ca outliers are deleted where citrus is missing (3B1–39; 3B2–101),

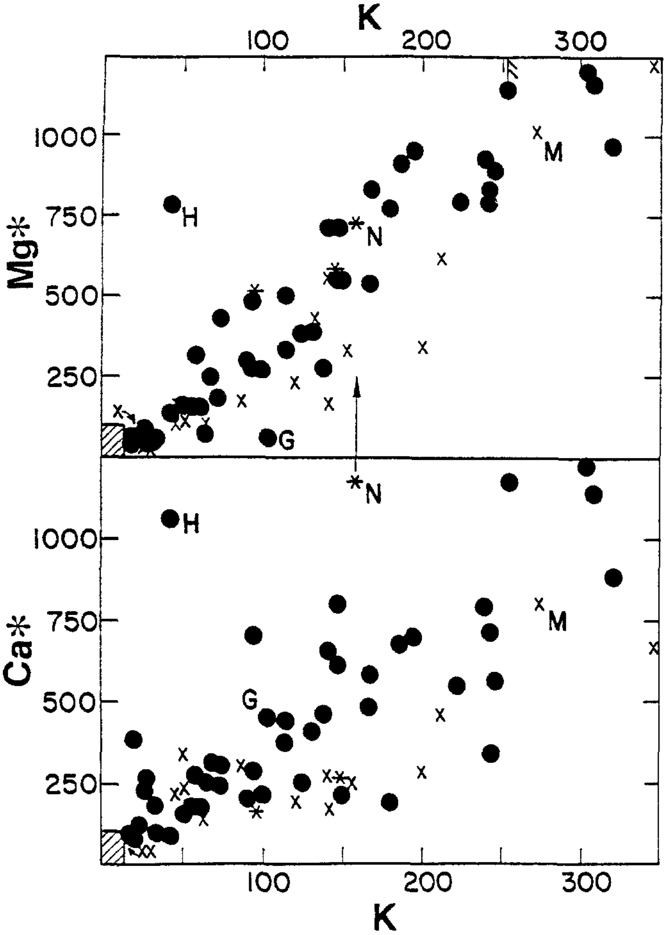


Fig. 4. As for Figure 3 but for Mg* (upper panel) and Ca* (lower panel). The hatched rectangles depict range of values for 3B1 & 3B2 lakes with K < 15 meq m^{-3}.

the correlation between Mg** and K**:

$$\text{Mg}^{**} = 15(24) + 3.70(0.13)\ \text{K}^{**} \qquad R^2 = 0.92 \tag{7}$$

remains significantly higher than between Ca** and K**:

$$\text{Ca}^{**} = 90(27) + 2.47(0.15)\ \text{K}^{**} \qquad R^2 = 0.79. \tag{8}$$

These equations reveal that Mg** > Ca** where K** > 65 meq m^{-3}. The statistical link between Mg** and K** (R^2 = 0.89; N = 76) is significantly stronger than between Mg** and Ca** (R^2 = 0.77).

Gran alkalinity (ANC) also increases significantly with K** or K (Figure 5, R^2 = 0.36). However, as in the case of Ca** (see above) this relationship is much stronger if two watersheds (3B1–39; 3B2–101) lacking citrus are excluded:

$$\text{ANC} = -38(31) + 2.21(0.17)\ \text{K}^{**} \qquad R^2 = 0.71. \tag{9}$$

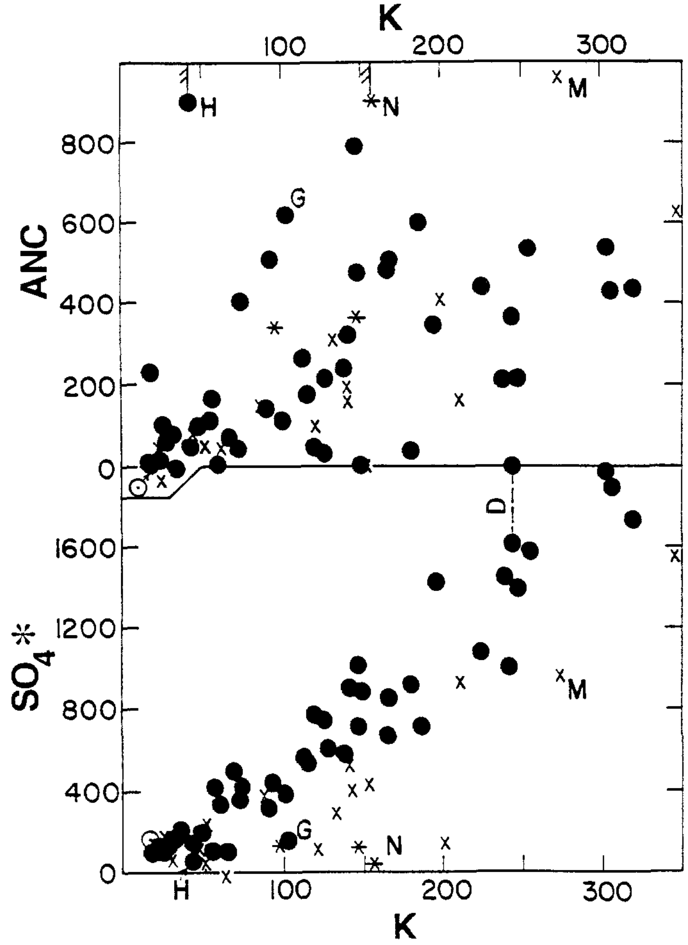


Fig. 5. As for Figure 3 but for ANC (upper panel) and SO_4^* (lower panel). The dashed line labeled D links points for Damon Lake (3B2–062).

The related residuals reveal no significant ($p > 0.1$) sub-regional contrast.

As might be expected from chemical principles, the regression model:

$$\text{ANC} = 0.954(0.019)C_B - 0.905(0.025)\text{SAA} - 0.103(0.014)\text{DOC} \quad R^2 = 0.98 \tag{10}$$

is much stronger than Equation (9). Here, the coefficients for base cations (C_B = Ca+Mg+Na+K) and strong acid anions (SAA = SO_4+Cl+NO_3) (by equivalents) are significantly ($p < 0.05$) smaller in magnitude than the theoretical value (1.0). By contrast, the coefficient for DOC is comparable ($p > 0.05$) to that for lakes in the northeastern and midwestern USA (Stauffer, 1990). Charge balance analysis reveals further that SO_4 is the most important 'acid anion' (54% of total) in these ridge lakes of central Florida, where on average it accounts for 10X the anions provided by DOC. By contrast, chloride accounts for 39% of acid anions.

Sulfate increases more sharply and consistently with K ($R^2 = 0.79$) than does ANC, making it the principal anion balancing the build-up of divalent bases in lakes with high K (Figure 5). However, unlike the relationships between Cl and K, or between ANC and K, here the best linear model features significant sub-regional contrast:

$$\mathrm{SO}_4^{**} = -223(58) + 4.50(0.21)\,\mathrm{K}^{**} + 358(56)\,\mathrm{Ind}_{\mathrm{HC}} \qquad R^2 = 0.87 \qquad (11)$$

where $\mathrm{Ind}_{\mathrm{HC}}$ is an ‘indicator’ (dummy) variable [= 1 for Highland County or 0 otherwise]. Not surprisingly, the statistical relationship between Mg^{**} and SO_4^{**} is also very strong, and retains a significant sub-regional contrast:

$$\mathrm{Mg}^{**} = 195(45) + 0.75(0.04)\,\mathrm{SO}_4^{**} - 202(49)\,\mathrm{Ind}_{\mathrm{HC}} \qquad R^2 = 0.84. \qquad (12)$$

3.3. EFFECTS OF CITRUS: MAJOR IONS

These statistical relationships among ions (Section 3.2.) are linked to land use. Citrus growing is important in the watersheds of all but 14 lakes with $\mathrm{K} > 15$ meq m^{-3}. Among these 14 exceptions, K was < 42 meq m^{-3} in 11 cases, and exceeded 65 meq m^{-3} in only two cases (K = 141, 158 meq m^{-3}). By contrast, among lakes with $\mathrm{K} > 250$ meq m^{-3}, citrus growing represented an exclusive cultural influence in every case but one (Mary, 3B1–045; urban drainage from Umatilla). Commercial citrus was also the dominant cultural influence throughout the mid portions of the K domain.

Because Cl^{*} averages 0 for the four undeveloped Highlands County watersheds, lakes satisfying the relationship $\mathrm{Na}^{**} = 0.86\ \mathrm{Cl}^{**}$ (marine ratio) can result from increased ECF due to spray irrigation. Irrigation water is frequently drawn from local lakes and shallow wells during the dry season (November–May), effectively recycling a portion of the abundant summer precipitation until the watershed ECF approaches the upper bound defined by regional *potential* evapo-transpiration (Jordan, 1984). By contrast, the four lakes in Highlands County used to estimate $\hat{\mathrm{Na}}_{\mathrm{bg}}$ (Equation (2)) were drainage lakes with relatively low Cl (mean = 183 meq m^{-3}), hence low ECF values (mean 8.5; computed as ratio of Cl concentration in lake compared to volume-weighted mean Cl concentration in precipitation at Lake Placid, Florida). The positive intercepts in Equations (3) and (4) show that higher ECF values prevail in the culturally-affected lake watersheds, even independent of K enrichment. The low ECFs for Lakes Silver (6.0) and Annie (7.5) are consistent with their hydraulic status as groundwater ‘flow-through’ lakes (Stauffer and Canfield, 1990).

The parameter values in Equations (3) through (6) cannot be explained by differences in evapo-concentration alone. However, they could result from differences in evapo-concentration, coupled with the effects of fertilization practices prevailing in Florida. On average, KCl accounts for 2X the $\mathrm{K_2O}$ applied in Florida, *vs* crude saltpeter (Table I). Assuming K = Na in the K-Na nitrate, and that the Cl and

Na are both quantitatively leached after application on the sandy soils, the Cl**:Na** might be expected to approach 2.0 for the ponds where fertilization is the dominant cultural influence on these two ions. This ratio will fall between 1.16 (marine ratio) and 2.0 if simple evapo-concentration is also a factor. Of course, individual lakes could vary depending on the specific fertilization practices of adjacent landowners (land foremen refused to divulge these to me).

This predicted stoichiometry is consistent with Equation (5); it also applies to small lakes surrounded by commercial groves ('citrus ponds') exhibiting maximum K($>$300 meq m^{-3}; Table II; Figure 3). As might be expected, neighboring ponds under common ownership exhibit similar ratios, as evidenced by the three Nellie Ponds (Lykes Corp; Highlands County; Cl**:Na** = 1.63 to 1.76). Similarly, samples 3B1–007 and 3B1–068 represent neighboring ponds, whereas 3B1–059 is located 2 km from the pair (Table II).

If grove fertilization with K salts were perfectly efficient, all of the added K would be extracted by the citrus crop, leaving no relationship between Cl** and K or between Na** and K. Instead we find highly significant ($p<0.01$) positive correlations for these solute pairs (Figure 3; Equations (3) through (6)). Nevertheless, the Cl**:K and Na**:K ratios decline at the upper K levels (Figure 3), suggesting that fertilization efficiency varies among the lake watersheds. Fertilization efficiency could be improved if the growers monitored the chemistry of the local 'citrus ponds' and adopted practices that were shown to increase Cl**:K and Na**:K. A similar potential exists for optimizing grove fertilization with inorganic-N (Section 3.4).

For lakes with K$<$50 meq m^{-3}, where citrus was a minor influence in the adjoining topographic catchment, Ca* increased more sharply than Mg* (Figure 4) and ANC increased more sharply than SO_4^* (Figure 5). Thus, Ca*:Mg*$\geqslant$1.0 (up to 7.0) for developed lakes lacking citrus. This situation represents the 'usual' water chemistry response to watershed development (e.g., Morgan and Good, 1988).

These initial solute trends changed abruptly for K$>$50 meq m^{-3} (Figures 4 and 5), at the point where citrus growing became the dominant cultural influence in the watersheds. The *major trends* depicted in Figures 4 and 5 and represented by Equations (7) through (12) are thus inextricably linked to citrus growing. We are thus fortunate to have detailed information on the growers' problems and practices in Florida (Ziegler and Wolfe, 1975), as summarized and interpreted below.

The successful cultivation of citrus on Florida's sandy ridge soils requires: (1) maintenance of a moderately acidic soil pH (5.5 to 6.5 is optimum); (2) intentional heavy fertilization with four 'major' nutrients (N, K, Mg, P), and, depending on specific site characteristics, a suite of 'minor' elements (e.g. Mn, Cu, Zn); (3) control of the Rust Mite (the single most important pest affecting Florida citrus); (4) irrigation during the dry season. These objectives are inter-related, and thus require an integrated management plan.

The native ridge soils are too acidic for citrus culture until amended by liming. Moreover, the Rust Mite can be controlled only by periodic spraying with wettable sulfur (S^o). The applied S is ultimately oxidized microbiologically to H_2SO_4, further increasing the acidity of the soil. The application of KCl also acidifies the soil as a consequence of the selective uptake of K by the crop (in exchange for H^+). Because citrus has a particularly high Mg requirement, and Mg is rapidly leached, the growers address the acidity and Mg requirement jointly by liming with dolomite. Nitrogen is the 'pivot element' in the fertilization program. Fertilization with saltpeter addresses both the K and N demands of the crop at low expense, while avoiding unnecessary additional acidification of the soil. Because the ridge soils are excessively drained, the seasonality of precipitation (Jordan, 1984) accentuates soil leaching. This leaching removes mobile cations (Mg^{2+}, K^+, Na^+) and anions (Cl^-, SO_4^{2-}, NO_3^-), but also prevents the build-up of Na, potentially resulting from fertilization with K-Na-NO_3 (saltpeter; Table I).

The above practices can account for all of the major solute trends depicted in Figures 2 through 5, and represented statistically by Equations (3) through (12). Citrus practices can thus explain the five enigmatic solute relationships listed in Section 1. In particular, they explain why SO_4 is a more important correlate of K and the divalent base cations than is ANC. Because the growers seek to maintain a moderately acidic soil reaction, ANC represents an ionic 'residual' where $CaMg(CO_3)_2$ (dolomite) is added to compensate for the acidifying influences of pest control and fertilization. Magnesium increases more consistently with K than does Ca partly because Mg and K are crop-limiting elements, sometimes added jointly as K-Mg sulfate (Table I). Moreover, both K and Mg are readily leached, whereas Ca is preferentially retained at the limited soil exchange sites where it serves to govern the soil's 'lime potential'. Like S, Ca is an important plant nutrient, but no specific provision is made for its fertilization because of the inadvertent additions as part of dolomite and superphosphate, and its superior retention in the soil.

As shown by Table II the solute enrichment patterns cannot be explained by withdrawals (pumping) from the underlying Floridan aquifer. This activity is economically uncompetitive in citrus districts where the *perched* water table finds frequent expression in doline lakes. However, Hog Lake (3B2–101) is the focus of a golf course and retirement community, and has been altered by pumping from the underlying Floridan aquifer. It appears as a major outlier in Figures 4 and 5a and was rejected as an outlier in Equations (7) through (9).

3.4. NUTRIENT RELATIONSHIPS: LAKE TROPHIC STATE

With few exceptions, NO_3 was < 2 meq m^{-3} in ELS-3B lakes with low K at December turnover (Figure 6a). Because NH_4-N was also low, inorganic-N was efficiently retained in Florida lake watersheds lacking significant development (Baker *et al.*, 1988). By contrast, extreme nitrate enrichment was prevalent among the small, deep, clearwater 'citrus ponds' with high K (Figure 6b; Table III). The 10 lakes with maximum NO_3 ranked near the bottom of the color distribution, i.e. equivalent to Lake Annie in the Archbold Preserve (Table III). These same NO_3-enriched citrus ponds lacked significant ammonia-N, and were dominantly of the 'seepage'

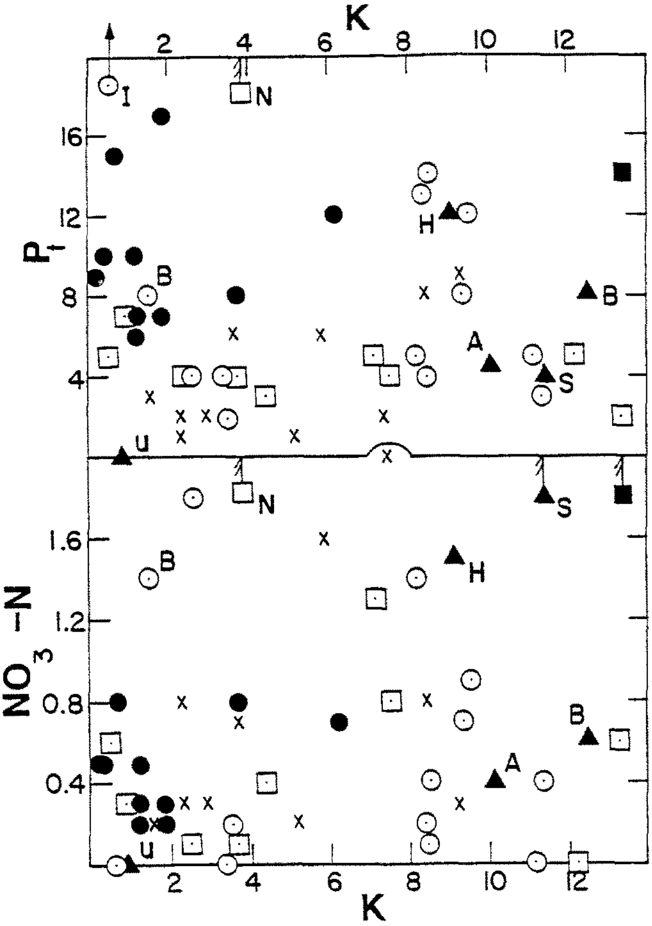


Fig. 6a. Total-P (P_t; mg m^{-3}; upper panel) and NO_3-N (meq m^{-3}; lower panel) *vs* K (meq m^{-3}) for ELS-3B1 & 3B2 lakes with low K. See Figure 2 legend for group symbols. Off-scale values: N (P_t = 32; NO_3 = 3.8); S (NO_3 = 3.0); Bullock (NO_3 = 16.8).

type (Table III). Elsewhere the nitrate distribution was bifurcated; approximately half of the lake samples had only traces of NO_3; the remaining samples were enriched over 'background' (e.g. Lake Annie) by about one order of magnitude (Figure 6). Figure 6b suggests that watershed export of soluble inorganic-N is low up to some fertilization threshold; thereafter the mobile nitrate ion 'breaks through' the barrier normally provided by the trees' root system. Nitrate was >K in only two lakes (Table III). Historically the growers have tended to overestimate the K requirement of crop as compared to N (Ziegler and Wolfe, 1975).

Total phosphorus (P_t) exhibited different patterns from that of N. There was no incidence of P enrichment in the deep, clearwater, seepage lakes set in citrus groves, where K and NO_3 characteristically attained their maximum concentrations (Figure 6b; Table III). Instead, P_t were highest in comparatively shallow drainage

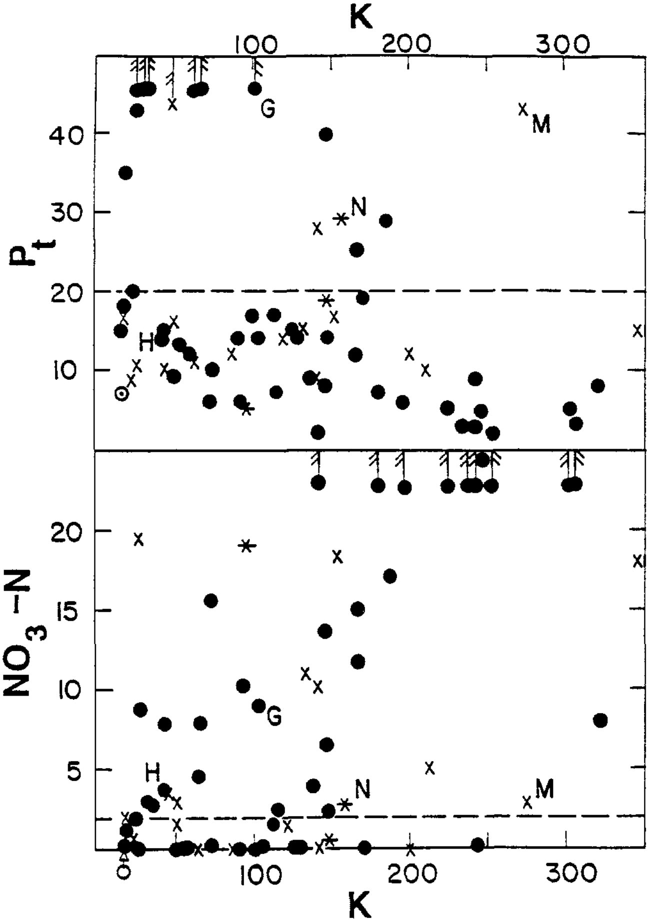


Fig. 6b. As for Figure 6a but for lakes with K>15 meq m^{-3}. The horizontal dashed lines denote top of ordinal scales in Figure 6a. See also Tables III and IV.

lakes with moderate K, in which color and DOC (dissolved organic carbon) were elevated, and cattle ranching and/or suburban development constituted the dominant cultural impacts (Table IV). All but three of the 26 lakes in Highlands County with $P_t >$ regional median (12 mg m^{-3}) were drainage lakes. Not one of these 26 lakes featured citrus as an exclusive cultural influence. Among the 18 lakes in the top quartile ($P_t > 20$ mg m^{-3}), citrus growing was missing in the watersheds of seven, and clearly of secondary importance in five other cases. Every lake in the upper quartile (P_t) also featured color $\geq$ 35 CPU (compare with Table III); the lakes in Table IV also included 8 of the 10 highest color values recorded by the EPA in Highlands County.

Multivariate regression revealed two factors related to P_t in Florida ridge lakes (ELS-3B1 and 3B2) lying south of 29° latitude, lake depth z and DOC (or color). Excluding Glenada, the best predictor ($R^2 = 0.51$, $N = 75$) was:

TABLE III

Physical-chemical features of EPA lakes with very high nitrate in Highlands County Florida

Lake name	Type[a]	EPA #	A_0	z	SDT	Color	K	NH_4	NO_3	P_t	SIN:P_t	Chl a[b]
(A) Lakes with high nitrate												
Simmons	S	105	8	14.6	5.7	5	254	0.4	494	2	7700	0.6
Isis	S	111	21	13.4	6.3	5	141	0.6	244	2	3800	0.5
Nellie-SE	S	033	11	12.8	1.8	15	303	5.8	236	5	1500	6.1
Byrd	C	074	19	9.1	6.3	10	239	0.8	218	3	2300	0.3
Denton	S	063	26	13.4	8.4	10	242	0.6	173	3	1800	0.1
Basket	S	024	22	8.5	5.8	5	307	1.3	106	3	1100	0.6
Brentwood	S	015	23	6.1	5.5	10	195	1.2	54.5	6	290	0.4
Viola	S	016	29	9.8	3.6	10	224	0.8	54.0	5	340	1.3
Angelo	S	020	22	4.6	3.4	5	180	1.7	33.5	7	150	2.5
Pioneer	S	067	34	9.1	3.7	10	246	0.7	24.4	5	150	1.2
(B) Deep Highlands lakes with low K												
Annie	D	053	34	12.5	5.3	8	10	6.7	0.4	5	44	0.5
Silver	D	107	8	7.6	4.8	5	11	0.1	3.0	4	24	1.0

[a] S = seepage; C = closed; D = drainage; SIN:P_t by atoms; P_t (total–P; mg m^{-3})

[b] Chlorophyll (mg m^{-3}) estimated from SDT and color (Canfield and Hodgson, 1983)

Ammonia-N and nitrate-N (meq m^{-3} or μM); other parameters as in Table II.

TABLE IV

Characteristics of EPA-ELS Lakes (3B1 & 3B2) with Maximum P_t

Lake name	Type	EPA #	A_0	z	SDT	Color	K	P_t	SIN:P_t	Chl *a*	Cultural Impacts
Glenada	D	019	74	9.1	1.1	70	102	495	0.6	7.5	U >> C
Huckleberry	D	025	47	7.3	0.6	105	27	256	1.2	27.5	L, U
Wolf	D	026	48	1.2	0.3	200	64	175	1.3	110.0	L, U
Charlotte	D	027	81	6.7	0.9	50	34	123	1.2	16.0	L, U
Sebring	D	022	188	3.4	0.4	100	32	64	2.0	85.0	U >> C
Istokpoga	D	048	11,174	1.8	0.9	75	68	60	4.4	12.0	U, L, C
Reedy	D	093[a]	53	3.4	0.2	225	51	57	2.5	>100.0	U, C
Josephine	D	029	494	1.8	0.9	100	27	43	0.5	9.5	L, U
Mary	S	045[a]	18	3.7	0.7	50	273	43	2.8	32.0	U, C
Bonnet	D	023	105	2.7	0.8	40	147	40	5.4	26.0	C, U
Ruth	D	113	33	6.4	1.6	65	19	35	2.0	3.0	L, U

[a] 3B1 (otherwise 3B2); See also Table III notes.
C = citrus; L = livestock; U = urban.

$$\begin{aligned} LP_t = {} & -2.45(1.03) - 0.27(0.15)\,\mathrm{Lz} + 0.82(0.13)\,\mathrm{LDOC} \\ & + 0.62(0.20)\,\mathrm{Ind}_{\mathrm{HC}}, \end{aligned} \qquad (13)$$

where the prefix *L* denotes the natural logarithm, and DOC has units μM. The indicator (dummy) variable for Highlands County was also significant ($p<0.05$). However, the indicator variable for drainage type (Ind_s = 1 if seepage lake; 0 otherwise) was *not* significant (partial-t = 0.12). Nor was K significant (partial-t = 1.18). The independence of K and P_t in these citrus districts is confirmed by Table V, which illustrates that recent secular trends in K in Highlands County lakes have not been matched by trends in P_t.

The statistical link between DOC (or color) and P_t extends to Florida ridge lakes (ELS–3B1 and 3B2) lying north of 29° latitude. Here, the correlation coefficient between LP_t and LDOC is 0.64. Canfield *et al.* (1984) also reported a significant positive correlation (r = 0.46) between color and P_t for an independent set of 165 lakes, representing all of the major physiographic regions of Florida.

The low P_t concentrations in Florida 'citrus ponds' apparently reflect efficient P retention in the soil, not fertilizer application rate. Ziegler and Wolfe (1975) recommend fertilizing bearing orange groves according to the N:K:Mg schedule: 13:4:7 equivalents per box of fruit, with a P:K ratio = 2.5 mg meq^{-1}. The P requirement

TABLE V

Time trends for K and P_t in Florida ridge lakes[a]

Lake name	Region & ELS I.D. #	Area (ha)	K sequence			P_t sequence		
			t_1	t_2	t_3	t_1	t_2	t_3
Compass	PH 3B3–185	33	8	10	2^{D}	2	6	2
Crystal	PH 3B3–184	73	5	5	4	9	6	6
Ocheesee	PH 3B3–132	65	5	8	9	9	8	9
Turkey Pen	PH 3B1–140	7	6	8	7	8	5	2^{D}
Cherry	NP 3B3–183	194	13	15	15	19	35	23
Ocean	NP 3B3–182	723	5	3	4	12	24	15
Magnolia	TR 3B1–141	81	4	3	3	1	9	4
Sandhill	TR 3B1–142	508	3	3	3	3	9	2
Sellers	ONF 3B1–077	160	8	8	7	1	3	5
Wildcat	ONF 3B1–143	133	3	3	4	11	2	5
Dinner	HC 3B2–094	152	94	118	147^{U}	12	7	8
Jackson	HC 3B2–092	1297	49	54	61^{U}	16	13	12
Josephine	HC 3B2–029	494	31	28	27	23	18	43^{U}
L. Redwater	HC 3B2–081	132	17	20	24^{U}	27	28	20^{D}
Lotela	HC 3B2–099	323	49	56	73^{U}	20	13	10^{D}
Placid	HC 3B2–089	1352	32	33	54^{U}	18	8	13
Red Beach	HC 3B2–054	134	30	37	43^{U}	17	13	15
Sebring	HC 3B2–022	188	21	26	32^{U}	147	76	64^{D}

[a] Units: K (meq m^{-3}); P_t (mg m^{-3}). Times: t_1 = Sep 79 – Jan 80; t_2 = Jun – Aug 80 (both, Canfield, unpubl.); t_3 = Dec 84 (ELS). Superscript D = downtrend; U = uptrend (p < 0.05). Regions: PH = Panhandle; NP = North Peninsula; TR = Trail Ridge; ONF = Ocala National Forest; HC = Highlands County.

is doubled during the first 10 yr of grove life, but eliminated after 20 yr. The comparatively low P:K ratio and the phased reductions reflect the natural abundance of phosphatic subsoils in central Florida and the efficient retention of P in the rooting zone (Ziegler and Wolfe, 1975). The growers formerly used fertilizer mixtures that were too rich in P and K (e.g. 3-8-8; standard reporting basis). Thus, the low P_t concentrations in the regional 'citrus ponds' cannot be attributed to P-poor soils and to low fertilizer application rates, either now or in the past. Assuming that watershed P_t loadings are proportionally represented in lake concentrations (the classical linear Vollenweider model), I infer from Figure 6b and Table III that the P_t export coefficient (mg P m^{-2} yr^{-1}) for citrus growing on these sandy ridge soils is comparable to that for the native scrub vegetation.

Hydrology evidently interacts with land use to govern lake P_t in the ridge provinces, and this P then acts as the principal determinant of lake trophic state (Tables III and IV). The SIN:P_t ratio is highly skewed among the 'citrus ponds'. These same ponds have pelagic trophic indices (P_t, SDT, Chl *a*) that are not significantly different from those for Lakes Silver and Annie (Table III), the most pristine deep lakes still remaning in the southern Highlands province. Ironically then, the watershed management practice featuring heavy overall fertilizer application rates (citrus) has a relatively benign effect on lake eutrophication.

What accounts then for the greater eutrophicating influence of suburban development and livestock operations, given the much lower K concentrations found in these lakes (Figure 6b; Table IV)? Based on site inspection I suspect that this difference mainly reflects the efficiency with which P_t is delivered to surface water, and is largely independent of *land* application rate. Thus, unlike in citrus groves where the nutrients are evenly spread around the tree bases set well back from the water's edge, suburban development preferentially affects the riparian zone, and also includes increases in impervious surfaces, and increased channelizing of the resulting runoff. Furthermore, septic tanks represent potent subterranean point sources of P often set comparatively close to the water's edge. For livestock the mode of enhanced P delivery to surface waters is different, but the net result is the same. In either case the critical nutrient flow paths are focused, short and shallow, as compared to diffuse, long and deep beneath the ridge groves.

3.5. CHEMICAL HYDROLOGY

The previous sections well illustrate one of the central tenets of limnology, namely that lake composition reflects processes in the catchment. However, the linkages between land use and lake condition (e.g. trophic state) can be made precise only if more information becomes available on the hydrology and solute retention coefficients in these regional lakes. This same information might also be exploited to maximize the efficiency of citrus fertilization practices, and minimize the negative externalities of watershed development.

In some lake districts seepage inflow can be estimated using tracers (Stauffer, 1985). A culturally-derived solute will serve optimally as a hydraulic tracer if it can be easily and precisely measured, and is highly mobile (quasi-conservative) in the migrating groundwater. In addition, the terrestrial application rate should be known, be uniform, and be greatly in excess of the 'background' deposition rate on the lake surface. For citrus districts of Florida the set of potential tracers might thus include: Cl, Na, Mg, Ca, K, and SO_4.

As one example, cultural tracers can be used to delimit the potential recharge areas for seepage lakes in ridge provinces of central Florida. Thus, based on air-photo reconnaissance of the near-shore environment, and on an hypothesized regional hydrogeologic model, Baker *et al.* (1988) described the ionic regulation of relatively pristine Florida ridge lakes. However, most of these lakes from central Florida were highly enriched in K and other agricultural tracers (e.g. 3B1–08, K = 211; 3B3–77, K = 129 meq m^{-3}). In all such cases, map reconnaissance reveals intensive agriculture (mainly citrus) in property set back from the lake margin. Tracer analysis thus indicates that the potential recharge areas (hence seepage inflow) were larger than assumed by Baker *et al.* (1988). Because these same lakes also had higher ANC values, I am led to question their models of ANC generation and Ca-enrichment in these Florida lakes. Additional research is called for on how lake area, depth, edaphic setting, and land use influence the ionic composition, trophic state, and contaminant loadings of Florida ridge lakes.

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