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Physical and Chemical Management Practices for Improving Water Quality in Channel Catfish *Ictalurus punctatus* Aquaculture

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Research on practices for improving water quality in channel catfish *Ictalurus punctatus* ponds was conducted at the Auburn University Fisheries Research Station, Auburn, Alabama, in 1998 and 1999. The objective of this two-year study was to determine better management practices to enhance water quality and improve production efficiency. In the first year, oxidation of bottom soil by drying, tilling, and applying sodium nitrate was performed (dry-till and dry-till with sodium nitrate treatments). The second year, based on the results obtained during the first year, precipitation of phosphorus (P) from water by applying gypsum was compared to the dry-till treatment (dry-till and dry-till with gypsum treatments). Control ponds were not subjected to bottom drying, tilling, sodium nitrate, or gypsum treatment. Channel catfish fingerings were stocked at 15,000/ha.

In the first year, water in ponds from dry-till and dry-till with sodium nitrate treatments had lower concentrations ($P < 0.01$) of soluble reactive P, nitrate (NO_3^-) and nitrite (NO_2^-) nitrogen (N), total ammonia (NH_3) nitrogen, total suspended solids and turbidity, and higher values of pH, Secchi disk visibility, total alkalinity, total hardness, and calcium (Ca^{2+}) hardness than water in control ponds. Ponds of the dry-till treatment also had lower concentrations ($P < 0.01$) of total P and total N than control ponds. Total fish production and survival rate did not differ among the treatments ($P > 0.05$). The findings suggested that drying and tilling pond bottoms between crops could achieve water quality improvement. Applying sodium nitrate to dry, tilled pond bottoms did not provide water quality improvement.

In the second year, the treatment with the best results from the first year, dry-till, was compared with a dry-till with gypsum treatment. Enough gypsum was applied to give a total hardness of about 200 mg/L, and gypsum was reapplied as needed to maintain the hardness. Compared to the control, dry-till and dry-till with gypsum treatments had lower concentrations ($P < 0.01$) of total and soluble reactive P, total N, and total NH_3-N, and higher concentrations ($P < 0.01$) of dissolved oxygen. Ponds of the dry-till with gypsum treatment also had lower concentrations ($P < 0.01$) of chlorophyll *a*, chemical oxygen demand, and total alkalinity than the control. Total fish production and survival rate did not differ ($P > 0.05$) among the treatments. These findings suggest that drying and tilling pond bottoms between crops and treating low hardness waters with gypsum could achieve water quality improvement.

Key words: Improving water quality, Channel catfish, Aquaculture

Introduction

Channel catfish (*Ictalurus punctatus*) farming has grown rapidly from a few thousand hectares in the mid 1960s to become the largest food-fish aquaculture industry in the United States (Hariyadi et al. 1994; Boyd and Tucker 1995; Boyd 1999; Anonymous 2000; Boyd et al. 2000). In 1998, slightly more than 250 thousand metric tons of channel catfish were produced in the United States. This is roughly double the amount

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produced a decade earlier (Boyd 1999). Mississippi and Alabama contribute heavily to the channel catfish production of the nation (Hariyadi et al. 1994). The catfish industry continues to grow, and there are good prospects for continued profitability.

Current management practices in catfish farming can be considered intensive, because average gross production was 3,354 (±1,810) kg/ha in 1996 (USDA 1997; Boyd et al. 2000). Intensive aquaculture practices can result in production as high as 7,800 to 11,200 kg/ha (Boyd and Tucker 1995; Wurts and Wynne 1995), but most farmers do not attain such high production. Intensive channel catfish culture with heavy stocking rates and feeding rates has attracted attention of environmentalists and created environmental concerns. Excessive nutrients and organic matter result in blooms of undesirable algae and deterioration of water quality in ponds, and lead to water pollution from pond effluents. Furthermore, large accumulations of nutrients, such as nitrite and ammonia, at the end of the summer can cause higher fish mortality resulting in considerable economic losses.

Both farmers and scientists are interested in finding ways to improve environmental conditions in catfish aquaculture. In many agricultural activities and some industries, it appears that using general permits or regulation by rule that includes best management practices (BMPs) will be more feasible than relying upon water quality standards (Schwartz and Boyd 1996; Boyd and Tucker 1998). The purpose of BMPs is to require that projects incorporate management methods that will prevent discharge or assure that effluents do not cause pollution or other environmental damage. The BMPs would not only improve environmental conditions in production ponds and enhance effluent quality, but they also would help to obtain better production under favorable water quality conditions. For example, high quality feeds without excessive phosphorus content should be used, and feed should not be applied in quantities greater than what the fish will consume. Good feeding practices that lower P inputs to ponds thus conserving the bottom soils ability to adsorb P. This practice should improve the ability of soil to remove P from the water and lead to lower availability of P to phytoplankton. Thus, good feed management should be an effective way of minimizing phytoplankton abundance in aquaculture ponds. There also should be additional benefits by minimizing problems with off-flavor associated with blue-green algae bloom, and pond effluent quality should be improved because it would contain less P, phytoplankton, organic matter, biochemical oxygen demand, and total suspended solids.

The objectives of this two-year study were to 1) measure the effect of oxidation of bottom soil with drying, tilling, and applying sodium nitrate on water quality and catfish production and 2) determine if gypsum applications to water in dry-till pond effectively reduce P in water and improve water quality and catfish production. Therefore, after this two-year study, some indication of better management practice can be discerned.

Materials and Methods

Ponds, treatments, and management

Ponds used in this study are located on the Auburn University Fisheries Research Unit (FRU) 10 km north of Auburn, Alabama at about 32.5° N latitude. They are 405 m^2 in area and rectangular with vertical concrete retaining walls around the edges. Ponds have average depths of 0.8 to 0.9 m, and maximum depths of 1.2 to 1.5 m. Water to supply the ponds flows by gravity through a pipeline from a large reservoir filled with runoff from a wooded watershed. Water levels were maintained about 10 cm below the tops of the standing overflow pipes to reduce the possibility of overflow during rains. Native soils are highly-leached, reddish-brown, and acidic (Masuda and Boyd 1994).

Twelve ponds for this study were drained for harvest in fall of previous years (1997 and 1998) and immediately refilled with water. In next spring (1998 and 1999), eight of the ponds were drained and the bottoms were dried for 1 month. Dry bottoms of four of the ponds were tilled to a depth of 20 cm with a roto-tiller (DT; dry-till treatment). Dry bottoms of the other four ponds were tilled, sodium nitrate (200 kg ha^{-1}) was broadcast uniformly over bottoms, and soils were tilled again to mix the sodium nitrate into the soil (DTS; dry-till with sodium nitrate treatment) in the first year. Four other ponds were dried and tilled, and after filling with water, enough gypsum (calcium sulfate) was applied to give a total hardness of about 200 mg/L as $CaCO_3$ in the second year. Gypsum was reapplied as needed to maintain total hardness (DTG; dry-till with gypsum treatment). Four ponds were not subjected to bottom drying, tilling or sodium nitrate or gypsum treatment (CONT; controls).

Channel catfish (*Ictalurus punctatus*) were stocked at the rate of 15,000 fingering ha^{-1} in 12 ponds. Fish were fed a commercial ration consisting of floating pellets (32-36% crude protein) at 3% of body weight per day. Daily feeding was performed in the morning, and the amount of feed in each pond was increased daily based on observation of feeding response on the previous day. Each pond had a 0.37 kW, vertical-pump aerator (Air-o-lator Corporation, Kansas City, Missouri) connected to a timer. Aerators were operated from midnight until 0600 h daily. Ponds were drained and fish harvested at the end of the September and October 1998, 1999, respectively. The total number and weight of fish in each pond were measured and recorded.

Water quality analytical methods

Water samples were collected weekly between 0600 and 0700 h with a 90-cm water column sampler (Boyd and Tucker, 1992) during the production period. Water temperature, dissolved oxygen, pH, and Secchi disk visibility were measured *in situ*. Water samples were stored in 1-liter plastic bottles and transported to the laboratory where analytical work was initiated immediately. A persulfate digestion procedure which allows simultaneous determination of total nitrogen by an ultraviolet spectrophotometric method and total phosphorus by the ascorbic acid method, was performed weekly (Gross and Boyd, 1998; Gross et al., 1999). Thereafter, water samples were further analyzed weekly for soluble reactive phosphorus by ascorbic acid method (Eaton et al., 1998), total ammonia (NH_3) nitrogen (TAN) by indophenol method (van Rijn, 1993), nitrate (NO_3^-) nitrogen (Szechrome NAS reagent; van Rijn, 1993) and nitrite (NO_2^-) nitrogen (Boyd and Tucker, 1992) by colorimetric methods. Chlorophyll a also was measured weekly by the acetone-methanol extraction method (Pechar, 1987), and chemical oxygen demand was analyzed biweekly by the heat-of-dilution dichromate oxidation method (Boyd, 1979). Gross primary productivity was analyzed biweekly by the light-dark bottle technique (Boyd and Tucker, 1992). Total suspended solids, turbidity, total alkalinity, total hardness, and calcium hardness were measured biweekly by methods described by Boyd and Tucker (1992).

Data analyses

Water quality data were analyzed among treatments with the Kruskal-Wallis One Way Analysis of Variance on Ranks, using dates as blocks to indicate if significant differences existed. Significant differences were further analyzed by the All Pairwise Multiple Comparison Procedure (Tukey Test) to determine which treatments differed. Production data were compared with one-way analysis of variance (ANOVA) with the Tukey Test. The 0.05 level of probability was used to declare differences. Statistical analyses were carried out using SigmaStat software V. 2.03 (SPSS, 1997).

Results

1. First Year

Water Quality

Temperatures in the ponds ranged from a low of 21 ℃ at the beginning of the study to a high of 30 ℃ in late June. Water temperatures were nearly the same in all ponds on each sampling date, and no differences among treatment as controls were ever noted.

The grand means for other water quality variables in ponds of the two treatments and the control are provided in Table 1. Mean concentrations of TP, soluble reactive P, TN, TAN, NO_3^- nitrogen, and NO_2^-

Table 1. Grand means standard errors of all water quality variables in 1998 from 400 m^2 channel catfish ponds at the Auburn University Fisheries Research Unit. Numbers followed by different superscript letters indicate significant difference with each treatment ($P < 0.05$). Two asterisks indicates highly significant difference ($P < 0.01$).

Dry-till	Dry-till with sodium nitrate	Control	*P*-value	
Total phosphorus (mg l^{-1})	0.34 ± 0.03^{a}	0.47 ± 0.04^{ab}	$0.55 \pm .04^{b}$	= 0.002**
Soluble reactive phosphorus (g l^{-1})	10.07 ± 0.93^{a}	17.02 ± 3.24^{a}	29.07 ± 4.49^{b}	< 0.001**
Chlorophyll *a* (g l^{-1})	153.02 ± 17.82	230.39 ± 24.75	144.88 ± 17.93	= 0.030*
Gross primary productivity (mg $l^{-1}day^{-1}$)	13.75 ± 1.45^{a}	16.47 ± 1.59^{a}	16.91 ± 1.57^{a}	= 0.296
Secchi disk visibility (cm)	27.59 ± 2.04^{b}	26.33 ± 2.06^{b}	17.23 ± 1.61^{a}	< 0.001**
Turbidity (N.T.U)	79.02 ± 10.63^{a}	94.68 ± 18.00^{a}	162.22 ± 15.43^{b}	< 0.001**
Total suspended solids (mg l^{-1})	56.94 ± 7.16^{a}	78.19 ± 14.69^{a}	105.06 ± 9.48^{b}	< 0.001**
pH	7.74 ± 0.03^{b}	7.63 ± 0.04^{b}	7.45 ± 0.03^{a}	< 0.001**
Total alkalinity (mg l^{-1})	80.95 ± 2.91^{b}	82.32 ± 4.05^{b}	55.80 ± 3.28^{a}	< 0.001**
Chemical oxygen demand (mg l^{-1})	30.71 ± 2.90^{a}	41.13 ± 3.94^{a}	35.89 ± 3.98^{a}	= 0.173
Dissolved oxygen (mg l^{-1})	5.68 ± 0.12^{a}	5.43 ± 0.13^{a}	5.47 ± 0.14^{a}	= 0.203
Total nitrogen (mg l^{-1})	3.34 ± 0.26^{a}	4.07 ± 0.35^{ab}	5.12 ± 0.37^{b}	= 0.001**
Total ammonia nitrogen (mg l^{-1})	0.93 ± 0.13^{a}	0.84 ± 0.14^{a}	2.14 ± 0.26^{b}	< 0.001**
Nitrate nitrogen (g l^{-1})	62.91 ± 12.80^{a}	30.78 ± 7.18^{a}	99.88 ± 11.98^{b}	< 0.001**
Nitrite nitrogen (g l^{-1})	79.25 ± 16.06^{a}	46.80 ± 10.20^{a}	82.76 ± 10.06^{b}	< 0.001**

nitrogen were lower in ponds of the DT than in the CONT ponds. However, ponds of the DTS did not differ from the CONT with regard to TP and TN concentrations. Thus, dry-till alone appeared to be a better treatment for reducing nutrient concentrations than dry-till plus sodium nitrate.

Total alkalinity of pond water was considerably greater in both treatments than in controls. The pH also averaged slightly greater in treatment ponds than in control ponds.

Secchi disk visibility averaged higher in ponds of both treatments than in control ponds, whereas turbidity and total suspended solids averaged less in ponds of both treatments than in control ponds (Table 1). These findings suggest that less particulate matter occurred in waters of treatment ponds than in those of control ponds. However, average chlorophyll *a*, gross primary productivity, and chemical oxygen demand values were not lower in either of the treatments than in the control (Table 1). Thus, in spite of lower concentrations of N and P in the DT than in the CONT, indices of phytoplankton abundance did not decrease in ponds of the DT.

Mechanical aeration was used nightly in an attempt to prevent low DO concentrations and stress or mortality of fish. Average DO concentrations were above 5 ㎎ l^{-1} between 0600 and 0700 h, and treatment differences did no occur. Nevertheless, in some ponds of treatments and controls, morning DO concentration declined below 2 ㎎ l^{-1}. Fish mortality that occurred in some ponds was the result of low DO concentration following aerator failure.

The changes in concentration of each water quality variable over time are provided in Figs. 1-6. Concentrations of TP (Fig. 1), chlorophyll *a* (Fig. 2), turbidity and total suspended solids (Fig. 3), total alkalinity (Fig. 4), chemical oxygen demand (Fig. 5) and the inorganic nitrogen fractions and TN (Fig. 6) generally increased as the study progressed in both treatments and control. Differences between concentration of variables in controls and treatments tended to be greatest late in the growing season for soluble reactive P, chlorophyll *a*, and chemical oxygen demand (Fig. 1,2, and 5). The opposite trend was observed for Secchi disk visibility, turbidity, and total suspended solids (Fig. 3). Concentrations of TN and TP and inorganic fractions of these two variables were lower in treatment ponds than in control ponds on most sampling dates (Fig. 1 and 6). Early in the growing season, chlorophyll *a* was lower ($P < 0.05$) in treat-

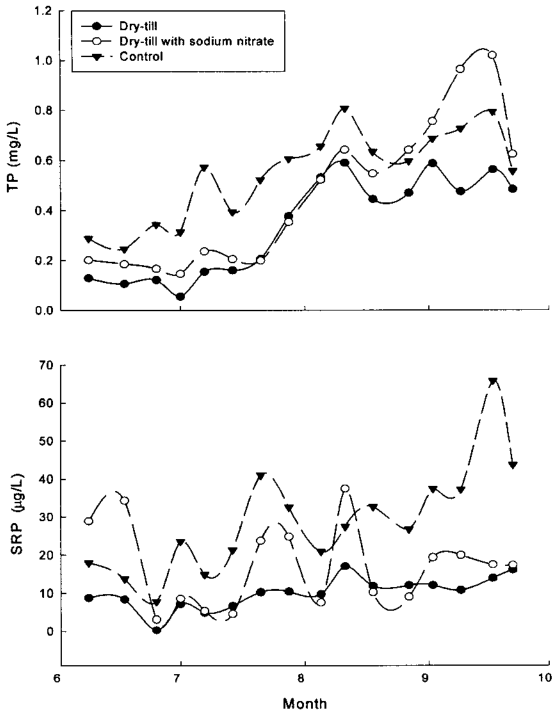

Fig. 1. Mean concentrations of total phosphorus and soluble reactive phosphorus in waters of channel catfish ponds in 1998.

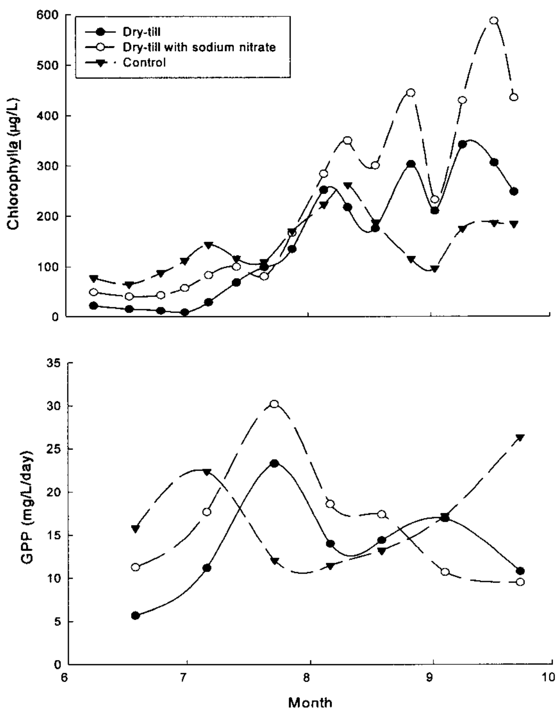

Fig. 2. Mean concentrations of chlorophyll a and gross primary productivity (GPP) in waters of channel catfish ponds 1998.

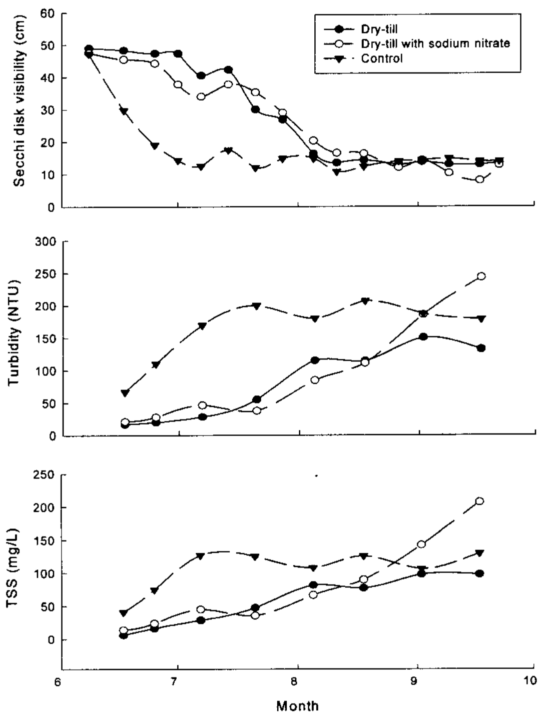

Fig. 3. Mean values and concentrations of Secchi disk visibility, turbidity in Nephelometer turbidity units (NTU), and total suspended solids (TSS) in waters of channel catfish ponds in 1998.

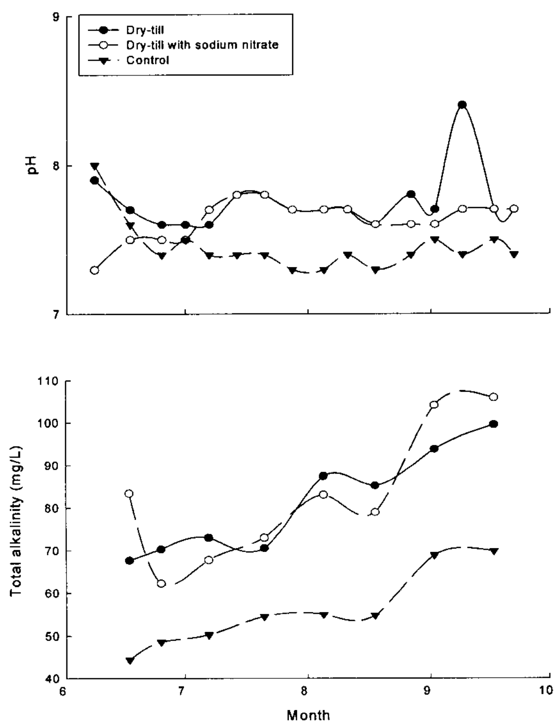

Fig. 4. Mean values and concentrations of pH and total alkalinity in waters of channel catfish ponds in 1998.

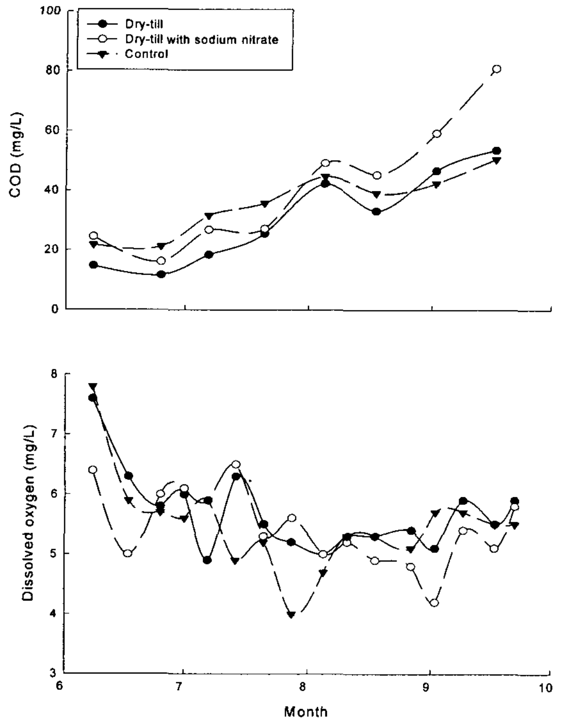

Fig. 5. Mena concentrations of chemical oxygen demand (COD) and dissolved oxygen in waters of channel catfish ponds in 1998.

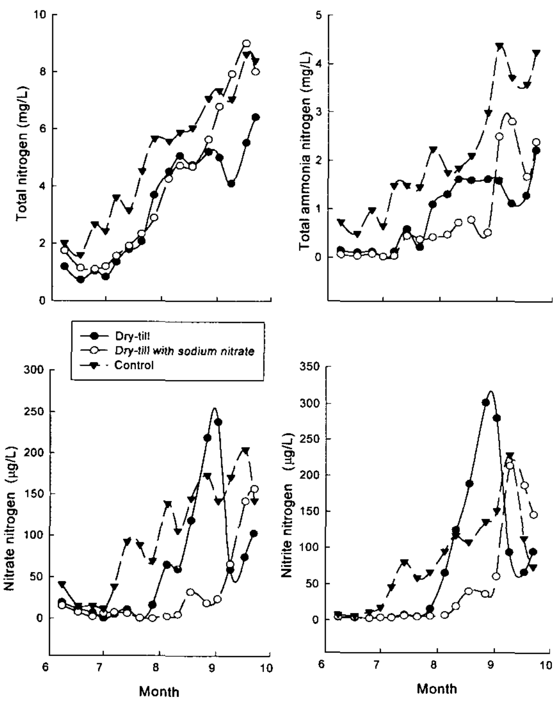

Fig. 6. Mean concentrations of total nitrogen, total ammonia nitrogen, nitrate nitrogen, and nitrite nitrogen in waters of channel catfish ponds in 1998.

ment ponds than in control ponds on several dates, but later in the growing season, the opposite trend was observed (Fig. 2). Secchi disk visibility was lower in the control ponds early in the growing season, but all ponds had similar Secchi disk visibility late in the growing season (Fig. 3). Turbidity was nearly always greater in control ponds than in treatment ponds, and total alkalinity always was higher in treatment ponds than in controls (Fig. 3 and 4).

Fish Production

There was an unexpected high mortality of fish in all ponds in late May and early June when fish became infected with proliferative gill disease and enteric septicema of catfish caused by *Edwardsiella ictaluri*. Mortality was essentially uniform in ponds of all treatments, and small fish for restocking were not available. One week before harvest, there was severe mortality of fish in one CONT pond and in two of the DTS ponds because of failure of aerators on two different nights. The mortalities occurred early in the night, and many dead fish were lost to scavengers before they could be recovered. Thus, accurate records on the numbers and weights of dead fish could not be obtained. When ponds were drained, it was found that overall survival and harvest weight of fish was highly variable among ponds and ranged from 4.6 to 84.5% and from 261 to 6,291 kg ha^{-1}, respectively. The DT ponds had the highest survival (64.6±16.3%) and the greatest average production (4,612±1,233 kg ha^{-1}). However, because mortality of fish just before harvest in the CONT ponds and in the DTS ponds was not related to treatment effects, the effects of treatments on fish production cannot be evaluated.

2. Second Year

The water temperature in ponds ranged between 16.1℃ at the beginning of the study to 30.3℃ in August. Water temperatures did not differ ($P > 0.05$) among treatment and control ponds at any time during the study.

Phosphorus and Phytoplankton

Mean concentrations of TP increased over time as feeding rates increased as a result of fish growth (Fig. 7). Soluble reactive P concentrations did not exhibit a consistent pattern of change during the study (Fig. 7). Depending upon the sampling date, individual ponds had from 3 to 76 times more TP than soluble reactive P. On average, TP concentrations were 12.8 to 16.9 times greater than soluble reactive P concentrations in the different treatments (Table 2).

Mean concentrations of total and soluble reactive P were greater ($P < 0.05$) in control ponds than in ponds of the other two treatments (Table 2). Differences in P concentrations between control ponds and treatment ponds were less between May and June than during the remainder of the grow-out period. For example, mean TP concentrations in DTG, DT, and CONT were 0.102, 0.132, and 0.144 mg l^{-1} between May and June and 0.219, 0.263, and 0.395 mg l^{-1} after June, respectively. In spite of gypsum application, mean P concentration did not differ between the two dry-till treatments ($P > 0.05$).

Phytoplankton abundance, as estimated from chlorophyll a concentrations, increased gradually and did not differ among control and treatment ponds until August (Fig. 8). During August, concentrations of chlorophyll a tended to increase at a greater rate in all

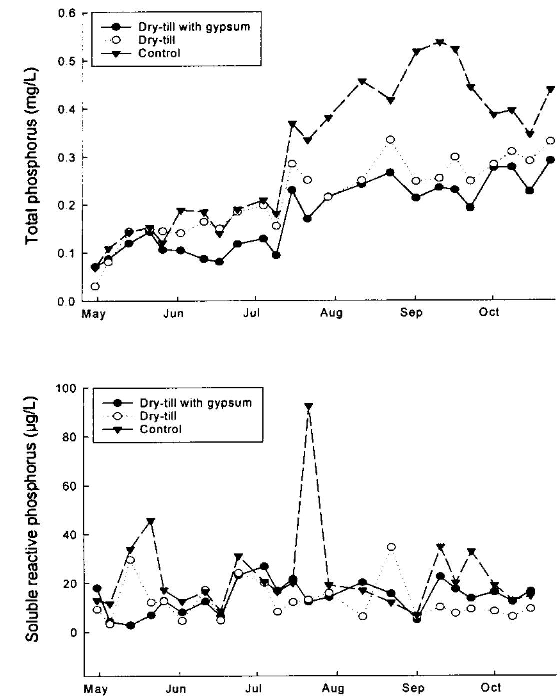

Fig. 7. Mean concentrations of total phosphorus and soluble reactive phosphorus in waters of channel catfish ponds 1999.

ponds, but the rate of increase was especially high in the control ponds. Chlorophyll a concentration declined

Table 2. Grand means with standard errors of water quality parameters in 1999 from 400m² channel catfish ponds at the Auburn University Fisheries Research Unit. Numbers followed by different superscript letters indicate significant difference with each treatment ($P < 0.05$). One-asterisk indicates significant difference ($0.01 < P < 0.05$), and two-asterisks indicates highly significant difference ($P < 0.01$).

Dry-till with Gypsum	Dry-till	Control	P-value	
Water temperature (℃)	24.38 ± 0.38^a	24.51 ± 0.37^a	24.33 ± 0.37^a	= 0.915
Dissolved oxygen (mg l^{-1})	6.96 ± 0.12^b	6.74 ± 0.11^b	6.16 ± 0.13^a	< 0.001**
pH	7.60 ± 0.04^a	7.75 ± 0.04^b	7.61 ± 0.04^a	< 0.001**
Secchi disk visibility (cm)	43.69 ± 2.72^a	38.82 ± 2.36^a	35.07 ± 1.88^a	= 0.250
Total phosphorus (mg l^{-1})	0.18 ± 0.01^a	0.21 ± 0.01^a	0.30 ± 0.02^b	< 0.001**
SRP (μg/L)	14.21 ± 1.47^a	12.39 ± 1.59^a	23.02 ± 3.88^b	< 0.001**
Total nitrogen (mg l^{-1})	1.95 ± 0.14^a	2.52 ± 0.16^b	4.28 ± 0.32^c	< 0.001**
Nitrate nitrogen (g l^{-1})	0.13 ± 0.02^b	0.08 ± 0.02^a	0.12 ± 0.02^{ab}	= 0.027*
Nitrite nitrogen (μg/L)	27.67 ± 5.60^a	20.27 ± 3.83^{ab}	33.66 ± 5.27^b	= 0.027*
Total ammonia nitrogen (mg l^{-1})	0.47 ± 0.10^a	0.56 ± 0.11^a	1.24 ± 0.19^b	= 0.003**
Chlorophyll a (g l^{-1})	57.00 ± 6.33^a	77.47 ± 8.81^{ab}	116.01 ± 14.50^b	= 0.006**
Chemical oxygen demand (mg l^{-1})	19.23 ± 1.20^a	27.99 ± 2.03^b	35.35 ± 2.92^b	< 0.001**
Total suspended solids (mg l^{-1})	45.79 ± 5.85^a	49.63 ± 5.72^a	52.96 ± 5.02^a	= 0.315
Turbidity (N.T.U)	50.53 ± 6.97^a	56.43 ± 6.58^a	72.21 ± 8.63^a	= 0.070
Total alkalinity (mg l^{-1})	36.90 ± 1.30^a	44.78 ± 1.31^b	45.25 ± 1.96^b	< 0.001**
Total hardness (mg l^{-1})	195.96 ± 6.60^b	48.13 ± 1.09^a	46.22 ± 2.11^a	< 0.001**
Calcium hardness (mg l^{-1})	162.13 ± 6.02^b	26.82 ± 0.79^a	24.06 ± 1.16^a	< 0.001**

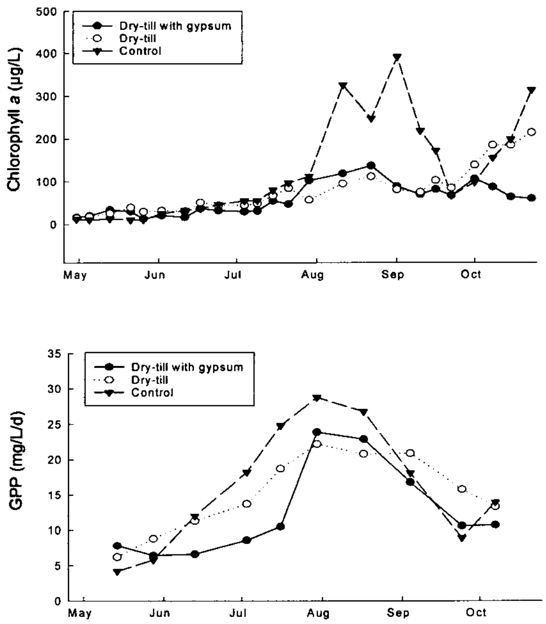

Fig. 8. Mean concentrations of chlorophyll a̲ and gross primary productivity (GPP) in waters of channel catfish ponds in 1999.

in all ponds in late August and early September but increased again in the CONT ponds and ponds of the DT in October (Fig. 8). Mean concentrations of chlorophyll *a* for the production period were less in the DTG than in the DT and the CONT (Table 2). Control ponds and the dry-till ponds did not differ in chlorophyll *a* (Table 2).

<u>*Turbidity and Total Suspended Solids*</u>

Secchi disk visibility decreased and turbidity increased in ponds until August and then remain somewhat stable (Fig. 9). Although the graphical data indicated lower Secchi disk visibility and greater turbidity in control ponds at times during the study, the means for the entire study did not differ among control ponds and ponds in the two treatments (Table 2). Mean total suspended solids concentrations were similar for the treatments and control (Table 2, Fig. 9).

<u>*Hardness, Alkalinity, and pH*</u>

Gypsum application usually maintained mean calcium hardness concentrations above 150 ㎎/L and mean total hardness concentrations above 180 ㎎/L, while in the other treatment and the control, mean values for these two variables were usually less than

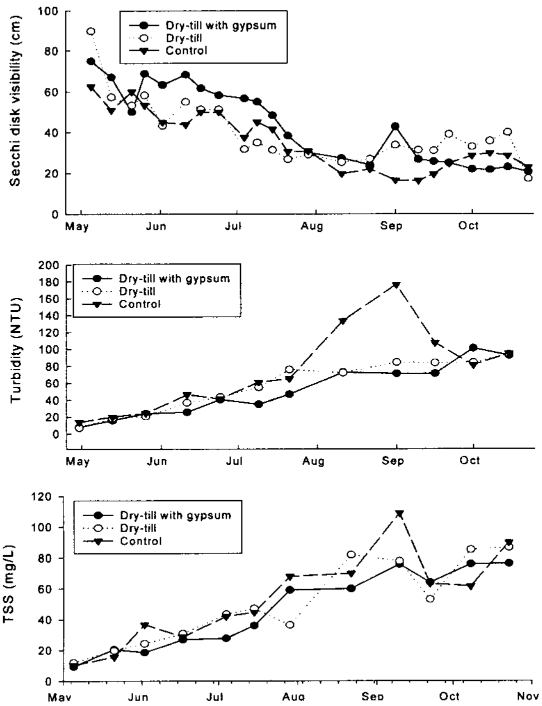

Fig. 9. Mean values and concentrations of Secchi disk visibility, turbidity in Nephelometer turbidity units (NTU), and total suspended solids (TSS) in waters of channel catfish ponds in 1999.

50 ㎎/L (Table 2, Fig. 10). Precipitation of calcium carbonate resulted from gypsum treatment, because the total alkalinity was lower on most dates in gypsum-treated ponds, and mean total alkalinity (Table 2, Fig. 11) was lowest in the DTG. The pH measured in the morning fluctuated considerably among controls and treatments over time, and the application of gypsum did not result in a lower pH than in the control ponds (Table 2, Fig. 11). The pH did not average above 8.2 in control or treatment ponds. However, pH was not measured in the afternoon when it would be expected to be the highest.

<u>*Oxygen Demand and Dissolved Oxygen*</u>

The chemical oxygen demand increased in controls and treatments as the study progressed, but the increase was greatest in CONT ponds, intermediate in the DT ponds, and lowest in the DTG ponds (Fig. 12). Means for the study revealed the same trends (Table 2). Chemical oxygen demand provides an estimate of dissolved and suspended organic matter in pond

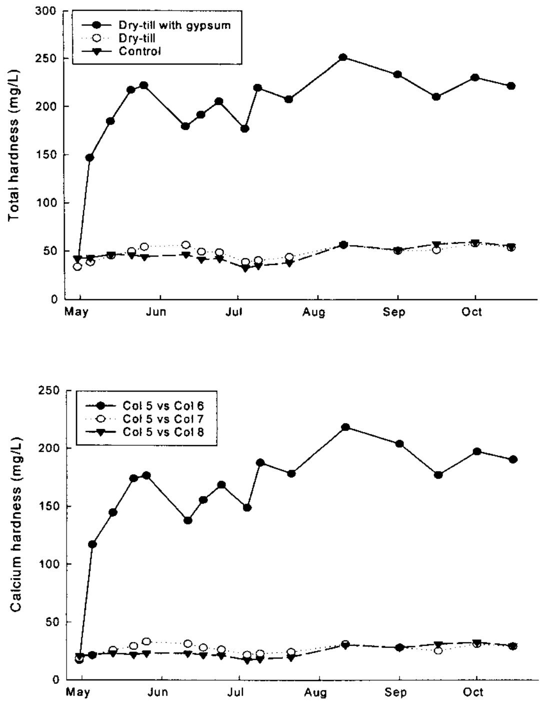

Fig. 10. Mean concentrations of total hardness and calcium hardness in waters of channel catfish ponds in 1999.

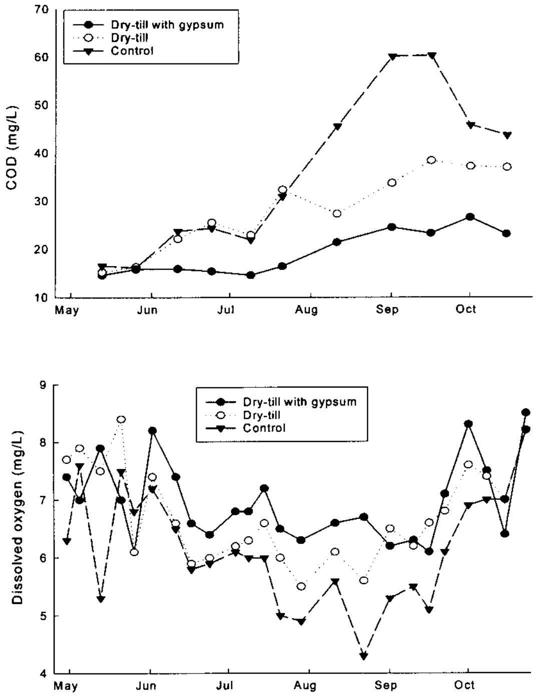

Fig. 12. Mean concentrations of chemical oxygen demand (COD) and dissolved oxygen in waters of channel catfish ponds in 1999.

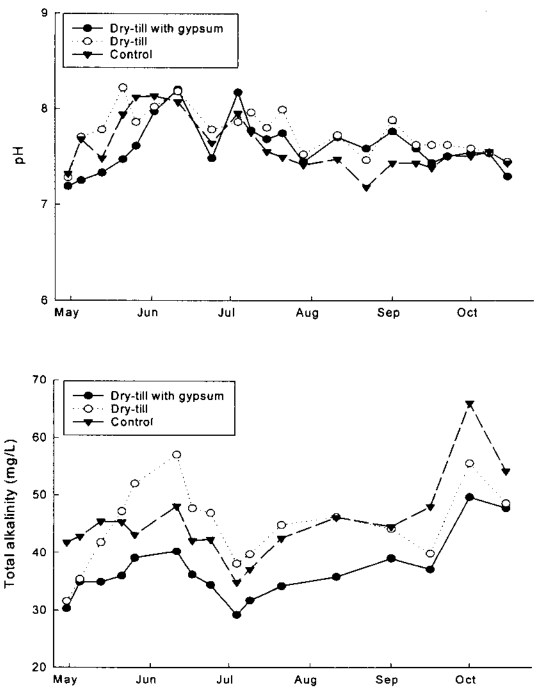

Fig. 11. Mean values and concentrations of pH and total alkalinity in waters of channel catfish ponds in 1999.

water, so this finding suggests that the DT reduces organic matter concentration and oxygen demand, but an even greater reduction can be achieved by combining gypsum application with the dry-till treatment.

Ponds were aerated nightly, and DO concentrations at dawn were usually above 5 ㎎/L (Fig. 12). However, there were a few dates between mid July and mid September when aeration was not adequate to maintain 5 ㎎/L DO. Nevertheless, treatment means below 4 ㎎/L were not recorded, and DO stress was not considered a factor in this study.

The DO concentrations do reflect oxygen demand, because the DT and DTG both had higher DO concentration than the CONT ponds during the critical period mid July to mid September. Mean DO concentration over the entire study did not differ between DT and DTG, but both of these treatments had higher concentrations than the CONT (Table 2).

__Fish Production__

Survival rates in individual ponds ranged from 75.8 to 96.2%, and survival was greater in CONT ponds

(89.9±3.0%) than in DT (84.5±3.0%), or DTG ponds (82.9±1.3%). The mortality of fish was related to disease and not to treatment effects. However, because of differential survival among ponds, harvest weight of fish was highly variable and ranged from 3,668 kg/ha to 5,621 kg/ha. Means for harvest weight were as follows: CONT, 5,105±293 kg/ha; DTG, 4,611±326 kg/ha; DT, 4,322±226 kg/ha. The means for harvest weight were not significantly different ($P > 0.05$) because of the variability in harvest weight within control ponds and ponds of each treatment.

Discussion

Findings of this study showed that drying and tilling of pond bottoms between crops could reduce concentrations of P and N in pond water during the following crop. When pond soils are dried and tilled, there is better contact with atmospheric oxygen to enhance microbial and chemical oxidation of organic matter and other reduced substances (Boyd 1995). When ponds that have been dried and tilled are refilled with water and used to produce another crop, there should be a less trouble with anaerobic conditions at the soil-water interface in ponds whose bottoms have not been subjected to this treatment. This should reduce the rate of release of P from iron phosphates, whose solubilities are favored by a low redox potential, and enhance the rate of P removed from water by soil particles (Masuda and Boyd 1994). Tilling of the soil should also increase the amount of soil surface exposed to the water, and this should enhance the soils ability to adsorb phosphate from the water.

The addition of sodium nitrate, an oxidant, to soils that had been dried and tilled did not further enhance their ability to remove phosphate from the water. This suggests that at the stocking and feeding rates used in this study, tilling alone is adequate to maintain oxidized conditions in the surface layer of bottom sediment. Sodium nitrate would not be useful as an oxidant until the dissolved oxygen concentration is practically depleted in the sediment (Boyd 1995). Gypsum applications maintained above 180 mg/L total hardness in the pond waters. Ponds on the Auburn University FRU have naturally soft water with total hardness concentrations of 8~12 mg/L. Ponds used in the present study have a 30-yr history of agricultural limestone treatment, and total hardness usually is 35~40 mg/L. Thus, it is impossible to recommend the total hardness (or calcium harness) concentration range over which gypsum treatment will be effective. We suspect that it could be effective to total hardness concentrations of 75 to 100 mg/L, but this suggestion should be evaluated on commercial fish farms. In Alabama, many channel catfish production ponds have total hardness concentration below 100 mg/L.

Masuda and Boyd (1994) showed that TP concentrations changed little with sediment depth within the upper 20-cm layer in ponds at Auburn University. Thus, tilling of the bottom to 20-cm depth, as done in this study, should not have influenced the concentration of TP in the surface layer by mixing the surface sediment with deeper sediment of higher or lower P concentration. Thus, tilling increased the ability of sediment to adsorb P rather than lowering its P concentration.

There also were markedly lower concentrations of turbidity and suspended solids and higher Secchi disk readings in the ponds that had been dried and tilled than in control ponds. It is likely that drying hardened the soil in the bottom and tilling encouraged the formation of stable soil aggregates and less dispersion of the fine soil particles. In ponds that were not dried, soft sediment remained from the previous crop and was resuspended in the water by mechanical aeration. Earlier studies at Auburn University in ponds where bottoms were not dried and tilled revealed that soft sediment is easily resuspended by aeration (Thomforde and Boyd 1991).

A highly oxidized pond bottom will adsorb the maximum amount of P from the water, and it will release less P to the water than a pond bottom with reducing conditions at the sediment surface (Masuda and Boyd 1994; Boyd 1995). Dry-tilling of pond bottoms provided for better oxidation of the sediment, and P concentrations were lower in both dry-till treatments than in the control. Although gypsum application to water has been reported to precipitate P as calcium phosphate (Wu and Boyd 1990), soluble reactive P and TP concentrations were no lower in the DTG than in the DT in the present study. Even though soluble and total P concentrations did not differ between the DT and DTG, there was less chlorophyll $\underline{a}$ and lower gross primary productivity and chemical oxygen demand in the DTG ponds than in the DT ponds. This suggests that P was made unavailable by gypsum treatment. There was continual input of P to the water of the ponds in fish excrement and uneaten feed. Phosphate in the water could react quickly with calcium to form calcium phosphate. Calcium phosphate particles are extremely small, and they would settle from the water slowly over a period of hours or possibly days (Bennett and Adams 1976). Daily aeration of ponds provided strong mixing which would help maintain the calcium phosphate particles in suspension. The methods used in this study for P analyses would not remove suspended calcium phosphate particles. Thus, the suspended phosphate would contribute to measured concentrations of both soluble reactive and total P. However, suspended calcium phosphate is not thought to be available to plants (Adams 1974), and this could explain why there was less phytoplankton activity in the DTG.

Channel catfish producers seldom drain production ponds after each crop, but fry and fingering ponds may be drained annually, and ponds for some other kinds of aquaculture are drained annually. Thus, the findings of this study suggest that when aquaculture ponds are drained, drying and tilling of the bottom can be an effective way of aerating soil and increasing the potential of P removal from pond waters. During the production period, periodic applications of gypsum could be made to reduce the availability of P in the water to phytoplankton. Of course, high quality feeds without excessive P content should be used, and feed should not be applied in quantities greater than fish will consume. Good feeding practices lower P inputs to ponds and conserve the bottom soils ability to adsorb P (Gross et al. 1998). Thus, DTG and good feed management can be an effective way of minimizing phytoplankton abundance in aquaculture ponds. These also should be additional benefits of minimizing problems with off-flavor associated with blue-green algae and pond effluent quality would be improved because it would contain less P, phytoplankton, and organic matter, biochemical oxygen demand, and total suspended solids.

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