Consequences of Decreased Water Temperature Caused by Aerator-Induced Evaporation on Growth of Pacific White Shrimp *Litopenaeus vannamei* in Ponds

by

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Abstract

Two studies were performed related to water temperature in aquaculture ponds. The first study evaluated the influence of aeration on evaporation and water temperature in ponds, and compared the effects of daytime and nighttime aeration on pond evaporation and water temperature. Water temperature and water loss by evaporation were monitored in ponds with different rates of aeration (9.2, 18.4, 27.6 and 36.9 kW/ha). The mean decrease in water temperature at 70-cm depth was greater than that at the surface in aerated ponds than in control ponds. Nevertheless, the mean decrease in water temperature at 70-cm depth was greater during daytime aeration than during nighttime aeration. The decrease in surface temperature was greater during nighttime aeration than during daytime aeration. The greater the aeration rate during either day or night, the cooler was both surface and water at 70 cm. Increasing the aeration rate also increased pond evaporation. Pond evaporation increases water loss by 32 and 92% over 24 h in ponds aerated with one and four 0.37-kW Air-O-Lator aerators, respectively. The nutrient-enriched control pond was more turbid, had cooler surface and deep water temperature, and had greater evaporation loss than the control pond without nutrient addition and less turbid water.

The second study determined water temperature patterns on a shrimp farm in different ponds and different years and revealed the effects of bottom water temperature in ponds to variation in shrimp performance. The study was conducted at Greene Prairie Aquafarm located in west-central Alabama. Water temperature at 1.2 m depth in 22 ponds and air temperature were monitored at 1-h intervals during the 2012, 2013, 2014 and

2015 growing seasons. Records of stocking rates, survival rates, and production were provided by the farm owner. Correlation analysis and linear mixed model analysis of variance were used. Results showed that the hourly water temperatures were different among ponds. The range of water temperature in each pond explained 41% of the variance in average final weight of shrimp harvested from each pond. In conclusion, results suggest that variation in water temperature patterns has a major influence on shrimp performance in ponds.

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Chapter 1 Introduction

Aquaculture is one of the fastest growing animal food sectors. One of the prime requirements to cope with the present demand for fish protein is intensification. The aquaculture intensification is performed by increasing the rearing density of fishes to increase the productivity per unit space. Maintaining good water quality is of particular concern in intensive aquaculture systems. In intensive and semi-intensive aquaculture operations, after meeting the culture animal's food requirements, low concentration of dissolved oxygen usually is the first major factor limiting production. Therefore, mechanical aeration becomes essential to allow greater availability of dissolved oxygen and support higher production.

Mechanical aeration is the most effective mean of increasing oxygen availability. Aerators increase the surface area of contact between air and water, thus enhancing the oxygen transfer. The use of mechanical aeration in aquaculture ponds is becoming increasingly common and more intensive. In earth-lined culture ponds, aeration rates in feed-based aquaculture may reach 25 – 30 hp/ha, but in plastic lined biofloc technology ponds were 100 hp/ha of aeration may be applied.

Increasing the area of contact between water and air to facilitate oxygenation also will increase the opportunity for evaporation. Although it is obvious that increasing the aeration rate will increase the rate of pond evaporation, the evaporative loss that results from using the mechanical aeration in aquaculture ponds or outdoor tanks has not been studied. Moreover, evaporation is a cooling process and the effect of mechanical aeration on water temperature in aquaculture systems is not known. Greater water loss from culture systems increases the amount of water required for aquaculture. Water shortages are becoming increasingly common in the world, and food production consumes the greatest proportion of the world's water annually. Thus, as with all kinds of food production, aquaculture should strive to reduce water use per unit of production.

Water loss caused by aeration should be taken into consideration during the planning phase of farm, to allow better estimation of the required capacity of water pumps from water budget calculations. In addition, evaporative loss increases the water salinity which can affect the growth and survival of the cultured shrimp and other marine culture species.

Culturing of Pacific white shrimp (*Litopenaeus vannamei*) in inland ponds supplied with low-salinity water is an increasing practice worldwide. The major challenge which is facing this method of shrimp production is the variation in growth, survival, and yield among ponds. There is not much information about the contribution of variation in water temperature on the variation in shrimp performance.

Thus, the overarching goals of this dissertation research were to evaluate the influence of aeration on evaporation and water temperature in ponds, to compare the effects of daytime and nighttime aeration on pond evaporation and water temperature, to determine water temperature pattern in different ponds and different years on a shrimp farm, and to evaluate the possible contribution of bottom water temperature to variation in survival, growth, and production.

Chapter 2 Literature Review

2.1. Water Loss

Aquaculture is water-intensive, requiring more water per unit area than other agriculture practices (Boyd, 1984; Likens, 2009). Measured in terms of evaporation and seepage from ponds or lakes, a kilogram of fish produced requires 0.4–1.6 m^3 of water. Extensive aquaculture can be very water intensive with a water requirement of up to about 45 m^3 per kilogram of fish, which is comparable to the water requirements to produce red meat. It is estimated that consumptive use of water for fish production is about 8% of withdrawals for irrigation (Likens, 2009).

Most aquaculture ponds are constructed by building dams to impound water. These ponds are mainly filled with ground water from wells and receive almost no runoff (Boyd, 1982, 1986). Because of the increasing demands on water resources and the rising costs of operating water supply systems, the studies of the hydrology of fish ponds is becoming essential (Boyd and McNevin, 2015).

The annual water requirements for pond aquaculture in the United States were calculated for 43 sites in 14 states, and the values ranged from 48.3 cm at Fairhope, Alabama, and Tallahassee, Florida, to 251.5 cm at Bakersfield, California (Boyd, 1986). Generally, the values were more than 191 cm/year in California, between 102 to 191 cm/year in Kansas, Texas, and Oklahoma, and between 76 and 102 cm/year in the southeastern United States (Boyd, 1986). An accurate knowledge about the consumptive use through evaporation is essential, especially in places where water resources are limited (Brutsaert, 1982). Consumptive use, also known as water consumed or water depleted, can be defined as the part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment (Lehr et al., 2005). The amount of water required for fish farming increases in a drier climate (Boyd, 1986) and, consequently, increases the costs of pumping from wells.

Evaporation and seepage are the major causes of water loss from ponds (Boyd, 1986). Seepage rates differ greatly among ponds because of construction practices and soil texture. Even ponds in the same vicinity may have great differences in their seepage rates (Boyd, 1986). Evaporation is the phenomenon by which the liquid water is converted into water vapor (Brutsaert, 1982; Gray, 1970; Hasfurther and Haass, 1986; Lehr et al., 2005) and transferred to the atmosphere (Hasfurther and Haass, 1986), including vaporization from water surfaces, land surfaces, and snow fields, but not from leaf surfaces (Lehr et al., 2005). Within the same climatic region, evaporation is more predictable than is seepage (Boyd, 1986).

Water entering the evaporation phase of the hydrological cycle becomes unavailable and cannot be recovered for further use until it condenses to form rain water (Brutsaert, 1982). Evaporation is a crucial factor in the determining the required water supply for fish ponds in both humid and arid climates (Boyd, 1986; Brutsaert, 1982). A non-covered body of water exchanges heat with the atmosphere via four mechanisms: evaporation, convection, radiation and conduction (Rafferty, 1986). Evaporation is solely responsible for much more than 50% of the total heat loss from a free water surface (Sartori, 2000), and it is the largest component of the total heat loss from the pond (Rafferty, 1986).

The annual precipitation exceeds pond evaporation in most areas in the southeastern United States. However, during most months in summer, fall, and spring, pond evaporation is greater than precipitation. Consequently, to maintain constant water level, water must be added to ponds during warm months. In some states such as Texas, Oklahoma, Kansas, and

California, pond evaporation exceeded precipitation year around (Boyd, 1986). It is difficult to estimate the quantity of evaporation from free water surfaces on a regional basis (Brutsaert, 1982). It is important to determine evaporation on the basis of meteorological data and independently from the water budget because unavoidable – relatively small – errors in measuring precipitation and runoff can often result in large errors in the resulting evaporation. Neglecting the nighttime evaporation can be a significant source of error in estimating evaporation (Iritz and Lindroth, 1994).

When water evaporates from lakes and streams, dissolved minerals are more concentrated in the water that remains. Each of these natural processes changes the water quality and potentially the water use (Lehr et al., 2005). The high evaporation losses contribute to the increase in turbidity of water (Msangi, 2013).

2.2. Evaporation Process, Estimation, and Measurement

Evaporation is one of the main phases of the hydrological cycle (Brutsaert, 1982; Malek, 1992). Water is continually evaporating from moist soil, streams, ponds, lakes and from oceans. Evaporation is like a commercial transaction in which a wet surface sells water vapor into its environment in exchange for heat (Monteith, 1965). Evaporation estimates are needed in a wide array of problems in hydrology, agronomy, forestry and land resources planning (Singh and Xu, 1997).

The problem of determining rate and amount of evaporation from water surfaces is rendered complex by the fact that the water becomes an invisible gas which rapidly mixes with the other gasses of the atmosphere and is transported large distances and to great heights (Thornthwaite and Holzman, 1939).

There is a vertical gradient in vapor pressure above the water surface (Gray, 1970). Clearly, evaporation depends on the supply of heat energy and vapor pressure gradient, which, in turn, depend on meteorological factors such as temperature, relative humidity, barometric pressure, wind velocity, solar radiation, quality of water, and the nature and shape of the evaporating surface (Morton, 1968). These factors also depend on other factors, such as geological location, season, etc. Therefore, the process of evaporation is rather complicated (Singh and Xu, 1997).

Three requirements must be met to permit continuous evaporation: a continuously moist surface in contact with air, a supply of energy to provide the latent heat of vaporization and a sink for removing the vapor. The second and third of these requirements are the theoretical basis for approaches to measuring evaporation from surfaces. First, energy balance approach in which evaporation is estimated from the energy budget. Second is the aerodynamic approach – sink strength – in which evaporation is regarded as the result of turbulent transport of vapor by a process of eddy diffusion. The former approach was found to be more successful (Penman, 1948).

Methods used to estimate the amount of evaporation from a free water surface can be grouped into five categories: mass balance or mass transfer equations (aerodynamic methods), energy balance or energy budget methods, water budget, empirical formulae, and measurements from evaporation pans (Gray, 1970). The conventional methods for estimating evaporation (empirical formula and pan estimates) can give erroneous results in arid environments (Hasfurther and Haass, 1986).

Evaporation is the link between the water budget and the energy budget (Brutsaert, 1982). Solar radiation is the engine driving the evaporation process. The sun provides solar energy to change liquid water to water vapor (Boyd, 2015). Dalton (1802) was the first to point out that evaporation is proportional to the difference between the vapor pressure of the air at the water surface and that of the overlying air. The driving force of evaporation is the vapor pressure deficit (VPD):

$$VPD = e_s - e_a$$

where e_s = saturation vapor pressure (the maximum amount of moisture that air can hold at its temperature), and e_a = actual vapor pressure.

When unsaturated air is brought into contact with a water surface, water molecules bounce from the water surface into the air. The greater the VPD, the greater is the potential for evaporation. The rate of evaporation from a unit surface of the water is proportional to the difference between the vapor pressure of the liquid and the vapor pressure of the surrounding air (Gagge, 1937; Winslow et al., 1937). The dependence on VPD during nighttime was similar to the dependence during daytime but with a much larger sensitivity during the dark period (Iritz and Lindroth, 1994).

Evaporation ceases when the vapor pressure is equal to the pressure of water molecules escaping the water surface (VPD = 0). Molecules of water continue to move across the surface, but there is no net movement in either direction (Boyd, 2015). Similarly, some of the water molecules contained in the water vapor in the atmosphere that are also in motion may penetrate the water surface and remain in the liquid. The net exchange of water molecules per unit time at the liquid surface determines the rate of evaporation (Gray, 1970).

Water temperature tells about the average kinetic energy of the water molecules. Losses can occur by evaporation even when the temperature is at or below the surrounding air temperature (Rafferty, 1986); so, water evaporates readily below 100°C. In a mass of water, the molecules are in constant motion. At a given temperature, water molecules are not moving at the same speed. The faster-moving molecules contain sufficient thermal energy to evaporate (Boyd, 2015). Water molecules have large latent heat of vaporization, which is 540 calories per gram of water evaporated at 100°C (Gray, 1970). Therefore, evaporation involves the transfer and redistribution of large amounts of energy under nearly isothermal conditions (Brutsaert, 1982; Lehr et al., 2005).

To relate the state of the environment to the rate of evaporation from a free water surface, some elementary principles of thermodynamics are needed. In natural evaporation, the state of a given mass of air can be described by its temperature *T* and its vapor pressure. The total heat content of the air is the sum of the sensible heat content, depending on temperature, and a latent heat, depending on vapor pressure. The rate of evaporation from a water surface with temperature *T'* – temperature at which air becomes saturated – can be calculated from the rate of increase in the latent heat content of surrounding air at temperature *T* (Monteith, 1965).

The energy budget procedures (Gray, 1970) and mass transfer techniques (Thornthwaite and Holzman, 1939) for determining evaporation from water bodies require expensive instrumentation. The mass-transfer methods give satisfactory results in many cases (Thornthwaite and Holzman, 1939). The aerodynamic methods utilize the concept of eddy motion transfer of water vapor from an evaporating surface to the atmosphere (Singh and Xu, 1997) and is based on the Dalton equation, which for free water surface can be written as:

$$E_0 = C\,(e_s - e_a)$$

where E_0 = free water surface evaporation, e_s = the saturation vapor pressure at the temperature of the water surface, e_a = the vapor pressure in the air, and C = aerodynamic conductance. Sometimes C is taken as:

$$C = 1/r_a$$

where r_a is the aerodynamic resistance and . The parameter C can also be construed as the amount of water evaporated from unit VPD (Morton, 1990; Singh and Xu, 1997), and it depends on the horizontal wind speed, surface roughness and thermally-induced turbulence (Singh and Xu, 1997).The aerodynamic conductance increases with increasing vertical velocity in the overpassing air (Morton, 1990).

Evaporation from a water reservoir can be estimated by measuring the differences of input and output energy fluxes (Gray, 1970). Evaporation as a latent heat flux (L_e) plays a crucial role in governing the weather and the climate. The sensible heat flux (H) is generally treated together with the rate of evaporation (E) (Morton, 1990). Observations of evaporation from lakes, reservoirs, and pans have been used in the development of many empirical formulae in which evaporation is expressed as a function of various meteorological data (Thornthwaite and Holzman, 1939).

One of the useful meteorological and climatological parameter is the Bowen ratio, which is the ratio of these two fluxes, $B_o = H/L_e E$ (Brutsaert, 1982). The Bowen ratio is proportional to the ratio of the difference in temperature to the difference in absolute humidity between instruments located at two levels above the evaporating surface (Morton, 1990).

Evaporation pans are widely used as a measure of evaporation in nature because they model the evaporation from a free water surface in a visible way (Brutsaert, 1982). Lake evaporation is often estimated from pan evaporation data (Gray, 1970). Many types of pans have been used over the years. The most common pans are the Colorado sunken pan, the class-A pan of the U.S. Weather Bureau, the sunken pan of the Bureau of Plant Industry, the GGI-3000 pan, and the 20-m^2 basin (Brutsaert, 1982). It is not possible to determine actual evaporation from free water surfaces by simply measuring the rate of loss of water from an exposed pan or atmometer (Thornthwaite and Holzman, 1939).

Pan evaporations may generate considerable differences in relation to a large water surface evaporation, depending on the surface length, absence of waves, and the rate of mass transfer (Sartori, 2000). Monthly evaporation rates for the pan are always greater than those for the pond (Boyd, 1985). The pan coefficient is used in practice as an adjusting factor for the pan observation to give an estimate of lake or pond evaporation (Hounam, 1973). The pan coefficient is given by the ratio E_{WB} / E_P, where E_P is the evaporation from pan and E_{WB} is the water body – lake or pond – evaporation (Boyd, 1985; Hounam, 1973).

There are seasonal variations of coefficients because of the difference between pan water temperature and air temperature, and between lake or pond water temperature and air temperature will vary seasonally (Hounam, 1973). The correlation between pan and pond evaporation improved when the longer span of times was considered. Monthly values had much stronger correlation than weekly and daily values did (Boyd, 1985). Climatic differences among regions influence the magnitude of pan coefficient (Hounam, 1973), and these differences also affect the validity of equations for estimating pond evaporation from solar radiation and water or air temperature (Boyd, 1985).

Beside pans, many other types of devices have been proposed and developed to measure evaporation. Better known among these are the porous cup atmometer, the Wild evaporimeter, and the Piche evaporimeter (Brutsaert, 1982).

2.3. Factors Affecting Evaporation

There are many factors that affect the rate of evaporation. The most important factors are temperature, relative humidity, wind velocity, dissolved salts, turbidity, atmospheric pressure, and the temperature difference between air and water. Temperature has the greatest influence on evaporation. Increasing temperature increases the molecular motion of the water and more molecules gain sufficient energy to escape the water surface, which favors evaporation. Evaporation rates are higher in warmer regions than those in cooler regions (Boyd, 2015).

The moisture holding capacity of air at a given temperature is limited. Therefore, the rate of evaporation is closely related to the relative humidity (RH %) of air. Drier air – lower RH % – has the capacity to evaporate more water than humid air (Boyd, 2015). The equations that do not take into account the RH, inaccurately predict the evaporation from the humid air, and the differences may be large in relation to the saturated state (Sartori, 2000). The equation to calculate relative humidity is $RH\ \% = 100\ (e_a / e_s)$. When the air is unsaturated, water will evaporate (increasing the latent heat content of the air) and the air will cool (decreasing the sensible heat content of the air) (Monteith, 1965). Warm air can hold more water vapor than cool air because the e_s increases with warmth. Cold, dry air may take on more moisture than warm, moist air (Boyd, 2015).

The speed of evaporation depends on the area of the evaporating surface. The rate of evaporation increases as the area of the evaporating surface increases (Mellor, 1922). The rate of evaporation from liquid drops that are suspended in the air is proportional to the diameter of the sphere rather than the surface area (Birdi et al., 1989). The rate of evaporation from a unit surface of the water is also proportional to the degree of air movement (Gagge, 1937; Winslow et al., 1937). When the wind moves slowly, the RH of air above the water surface increases, which will result in very small VPD. Consequently, very low evaporation will happen. While high wind velocity over water surface replaces moist air with drier air to favor evaporation. The influence of wind velocity on the rate of evaporation is obvious especially in arid regions (Boyd, 2015). Nighttime evaporation could be a major part of the 24 h evaporation in areas that experience high wind speed (Iritz and Lindroth, 1994; Malek, 1992).

Evaporation rate is independent of wind speed when water evaporates into the saturated air (Monteith, 1965). The equation to calculate evaporation when considering the wind speed is:

$$E = k\ (VP_s - VP_a),$$

where E = evaporative loss, VP_s = vapor pressure at the surface, VP_a = vapor pressure of the ambient air, and K = constant for a given wind velocity and air direction of application in relation to the water surface (Gagge, 1937; Mole, 1948; Penman, 1948). The rate of evaporation is exceptionally high whenever there is a combination of high temperature, very low RH, and strong wind.

Greater salinity causes a slight decrease in the evaporation rate (Sartori, 2000).The rate of evaporation from oceans is about 5% slower than that of freshwater because dissolved solids decrease the vapor pressure of water (Boyd, 2015).

Turbid water heats faster than clear water and dissolved solutes lower the vapor pressure of water (Boyd, 1985) Turbidity of water has no direct effect on the evaporation rate. However, the reflection of solar radiation may increase, and, thus, turbidity may indirectly affect the evaporation rate (Deodhar, 2008). Increased water turbidity and total dissolved solids favor evaporation (Boyd, 1985, 2015). Evaporation is influenced greatly by the phytoplankton density variations (Idso and Foster, 1974). The decrease in atmospheric pressure exerted on the water surface slightly increases the evaporation rate (Boyd, 2015).

2.4. Water Temperature in Aquaculture

The prediction of aquaculture pond temperatures throughout the year is essential to the design and evaluation of potential aquaculture sites (Calderón, 1989). Long-term meteorological data sets exist for many locations in the USA and can be used to develop predictive equations for water temperature (Green and Popham, 2008). A pond water temperature model was developed by Calderón (1989) to determine the potential for aquaculture. The predictors in this model were air temperature and global solar radiation under cloudless condition.

In the course of a year, in both tropical and temperate ponds, lowest temperatures were recorded sometime between 0200 and 1000 h and highest between 1200 and 2000 h (Young, 1975). The speed of changing the heat content of the water in a pond or tank is influenced by many factors, such as the minimum air temperature, the volume of water in the pond or tank, the volume of groundwater inflow, mechanical aeration, wind speed, and general weather conditions like cloud cover and precipitation (Green and Popham, 2008).

Seasonal changes in water temperatures, embracing periods of low, rising, high and declining temperatures, were recorded in both a temperate and a tropical pond (Young, 1975). In a temperate climate, seasonal changes in water temperature limit the optimum growing season to those within the appropriate water temperatures (Calderón, 1989). It is a common practice in pond culture to limit feeding during the colder months of the year because food consumption and conversion are poor when temperatures fall below 16-18°C (Andrews and Stickney, 1972).

The probabilities of a minimum air temperature ≤ 14°C can be used to guide pond management decisions for pond-cultured tropical species such as tilapia, *Oreochromis spp.*, and freshwater prawn, *Macrobrachium rosenbergii*, at the beginning and end of the growing season when intrusion of cold fronts may cause pond water temperatures to drop to critical levels. These probabilities can also be useful in planning for fish spawning, such as hybrid striped bass, *Morone chrysops* x *Morone saxatilis* (Green and Popham, 2008).

On clear days, during the hour centered at solar noon, the detailed down-welling solar radiation profile indicated that 48% of incoming minus reflected solar radiation was absorbed in the pond surface (Idso and Foster, 1974). The depth of penetration of solar radiation into a small pond is greatly controlled by the concentration of phytoplankton in the pond. Before the acceleration in the phytoplankton growth, light penetrated relatively well and resulted in moderate diurnal temperature variations. At the peak of phytoplankton concentration, when the light was excluded from the lower half of the pond, the surface layer exhibited much greater diurnal temperature variations, while the lower layer showed reduced variations.

Therefore, the severity of thermal stratification in the pond is controlled by the degree of light penetration (Idso and Foster, 1974).

Pond temperature has been shown to affect growth rates of channel catfish (*Ictalurus punctatus*) (Andrews and Stickney, 1972; Andrews et al., 1972; Stickney and Andrews, 1971). At temperatures less than the optimum, the growth rate increases as it nears optimum, reaching the maximum at an optimum temperature and decreases as temperature increases above the optimal (Calderón, 1989). Andrews and Stickney (1972) found no differences between growth rates of channel catfish fed three different feeding rates at temperatures below 22°C. However, at temperatures above 26°C, increasing feeding rates produced larger weight gains.

Stickney and Andrews (1971) obtained the maximum growth of channel catfish at 30°C. For channel catfish fingerlings, highest weight gains and best feed conversion efficiency were achieved at 30°C (Andrews and Stickney, 1972; Stickney and Andrews, 1971). Substantial gains were noted at 26 and 34°C with lesser gains at 18 and 22°C (Andrews and Stickney, 1972). Feed conversion ratios (FCR) ranged between 1.3 to 2.0 at temperatures of 24, 26 and 30°C, while higher ratios were obtained at low (20°C) and high (33°C) temperatures (Stickney and Andrews, 1971). FCR were the same at 22 and 26°C and were slightly higher than those achieved at 30°C (Andrews and Stickney, 1972). At high temperatures, the metabolic activity of channel catfish increased. Thus, conversion efficiency decreased which is the reason for the reduced growth at 33°C (Stickney and Andrews, 1971).

At 18°C, the feeding rate of 2% of biomass was not sufficient for maximum growth of fingerling, at 22 and 26°C, 4% produced maximum gain. At 30 and 34°C, additional growth was obtained by increasing the feeding rate to 6% (Andrews and Stickney, 1972). From fingerling to market size, the optimum temperature for growth and food conversion was between 28 and 30°C (Andrews et al., 1972). A growth model for channel catfish showed that food consumption increases linearly with increasing temperature (Calderón, 1989).

Baldwin (1957) investigated the effect of temperature on food consumption and growth rate of brook trout (*Salvelinus fontinalis*) and found that utilization of food consumed for growth declined with increase in temperature, and trout consumed most food and had the best growth at 13°C. The weekly consumption of minnows by the trout about doubled for each 4°C rise in temperature. The ratio of weight gain to food consumed showed a decrease with rising temperature. This decrease resulted from increasing demands on metabolites to meet maintenance requirements at higher temperatures.

The critical high water temperature – between 26°C and 29°C– was found to be an important factor in male gamete viability (Perez-Velazquez et al., 2001) in *L. vannamei*. They pointed out that the adequate sperm count and percentage of abnormal sperm of captive male *L. vannamei* broodstock can be maintained at a water temperature of 26°C, but not at 29 or 32°C.

Growth and feeding rate of Pacific white shrimp (*L. vannamei*), the most widely cultured species of shrimp, increased directly with temperature. The thermal effects on growth and feeding varied inversely with size. FCR of medium and large-sized shrimp varied with different temperatures (Wyban et al., 1995). Water temperature in acclimation tanks outdoors or lacking temperature control may drop to levels lethal to *L. vannamei*. The pond water temperature of 14°C appears to be a reasonable estimate for the lower lethal temperature of *L. vannamei*. One night with a minimum air temperature down to 14°C may cool water in ponds or outdoor tanks sufficiently to kill *L. vannamei*, particularly at night in partially full, aerated ponds. In Arcadia, Florida, during the third week of November, there is a high probability of a 1-d event when the minimum daily air temperature will be $\leq$ 14°C. While during most of December, there is a high probability of a 3-d event. These probabilities can be used to guide pond stocking and harvesting decisions (Green and Popham, 2008).

Temperature is one of the factors affecting the amount of fat in an aquatic animals body (Lovern, 1950). The environmental temperature affects growth, metabolism, and body composition of channel catfish (Stickney and Andrews, 1971). The environmental temperature had a noticeable effect on carcass lipid levels (Andrews and Stickney, 1972). Fish reared at the optimal temperatures for rapid weight gain contained a high percentage of lipid (Andrews and Stickney, 1972), which yielded lower dress-out percentages, and it is also undesirable from the standpoint of storage and consumer acceptance (Andrews and Stickney, 1972; Stickney and Andrews, 1971). An increase in environmental temperature from 18 to 34°C resulted in a nearly linear increase in the percentage of lipid content from 23.8 to 43.6% of the whole carcass (Andrews and Stickney, 1972). Stickney and Andrews (1971) found that the percentage lipid – on a dry weight basis– in fish carcasses increased with increasing temperatures up to 30°C, while the body lipid level decreased at 33°C. At the higher temperatures, food consumption is greater, body metabolic activity tends to be higher, with correspondingly greater energy expenditure. Therefore, more utilization of ingested fat rather than being available for storage (Lovern, 1950)

The efficiency of poikilotherms in assimilating and metabolizing saturated fatty acids is reduced at a lower temperatures (Stickney and Andrews, 1971). Reduced temperature resulted in a more unsaturated fatty acids (Lovern, 1950). Fish in cold water contain higher levels of polyunsaturated fatty acids (PUFA) (Stickney and Andrews, 1971). The levels of long-chain, highly unsaturated fatty acids, such as arachidonic and docosahexaenoic acid increased with decreasing temperatures. This increase is related to the physical properties of these lipids. These acids have relatively low melting points, can be absorbed, and transported at colder temperatures (Andrews and Stickney, 1972). Increasing temperature results in more saturated fatty acids (SFA), and, consequently, the PUFA/SFA ratio decreases (Lovern, 1950; Stickney and Andrews, 1971).

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Chapter 3 Effects of Mechanical Aeration on Water Temperature and Evaporation Rate in Aquaculture Ponds

3.1. Abstract

This study evaluated the influence of aeration on evaporation and water temperature in ponds and compared the effects of daytime and nighttime aeration on pond evaporation and water temperature. Water temperature and water loss by evaporation were monitored in ponds with different rates of aeration (9.2, 18.4, 27.6 and 36.9 kW/ha). The mean decrease in water temperature at 70-cm depth was greater than that at the surface in aerated ponds than in control ponds. Nevertheless, the mean decrease in water temperature at 70-cm depth was greater during daytime aeration than during nighttime aeration. The mean decrease in surface temperature was greater during nighttime aeration than during daytime aeration. The greater the aeration rate during either day or night, the cooler was both surface and water at 70 cm. Increasing the aeration rate also increased pond evaporation. Pond evaporation increases water loss by 32 and 92% over 24 h in ponds aerated with one and four 0.37-kW Air-O-Lator aerators, respectively. The nutrient-enriched control pond was more turbid, had cooler surface and deep water temperature, and had greater evaporation loss than the control pond without nutrient addition and less turbid water.

Keywords: Aeration, evaporation, temperature, aquaculture ponds

3.2. Introduction

Diffusion of oxygen from the atmosphere and oxygen from photosynthesis by aquatic plants often will not avoid low dissolved oxygen (DO) concentration in aquaculture ponds receiving large inputs of nitrogen and phosphorus from fertilizers and especially from feeds (Boyd and Tucker, 1998). Water exchange to replace oxygen-deficient water with water of greater DO concentration has been widely used as an emergency treatment for low DO concentration (Boyd et al., 2006; McGee and Boyd, 1983). However, mechanical aeration is more effective than water exchange for increasing DO concentrations (Boyd, 1998; Hopkins et al., 1993). The use of mechanical aeration has become a standard practice in feed-based culture of channel catfish *Ictalurus punctatus*, marine shrimp *Litopenaeus vannamei* and *Penaeus monodon*, and several other species.

Mechanical aerators function by splashing water into the air or by releasing air bubbles into the water creating a greater surface area for diffusion of oxygen between air and water. In addition, waves and ripples formed at the surface of a water body by aeration also facilitate oxygen transfer (Boyd, 1998). The most widely used aerators in commercial aquaculture are paddlewheel devices that splash water into the air. Paddlewheel aerators are not well-adapted for small, research ponds because of their relatively large size. Thus, vertical-turbine type aerators, diffused-air systems, and propeller-aspirator pump aerators commonly are used in small research ponds. Aerators cause currents that cause pond water to circulate and mix, therefore lessening the tendency for thermal stratification. Water circulation also favors the movement of oxygenated water across the sediment surface (Boyd and Tucker, 1998).

In general, the rate of physiological processes in aquatic animals increases as the temperature and DO concentration increase (Brett, 1979; Buentello et al., 2000). Growth rate is reduced if the energy demand of increased metabolic rate exceeds the gain from increased food consumption (Brett, 1979). When the food supply is not limiting, the specific growth rate of most aquaculture species increases with rising temperature (Talbot, 1993). But, temperature can increase above the optimum for a particular species causing growth to decline. In feed-based aquaculture production in ponds, nutrients entering water from uneaten feed, feces, and metabolic excretions result in abundant phytoplankton. Increasing temperature results in greater oxygen production by phytoplankton in pond water, but it also increases oxygen consumption by organisms in the pond. If the oxygen consumption rate exceeds the rate of oxygen production, the DO concentration may decline to a critical level (Kepenyes and Váradi, 1984). This situation can be avoided by mechanical aeration. Phytoplankton blooms tend to increase the temperature in pond water and especially near the surface (Idso and Foster, 1974). Mechanical aeration mixes water and avoids thermal stratification in ponds with plankton. Nevertheless, the temperature of the entire water column may increase as a result of mixing the higher temperature surface water with deeper water (Busch et al., 1978).

The rate of evaporation from pond surfaces is directly influenced by temperature, wind speed and the vapor pressure difference between the water and the air, while inversely related to the latent heat of vaporization and water density (Tucker and Hargreaves, 2009). Pond evaporation represented 66.2% of the total water loss from a channel catfish pond in Alabama (Brown et al., 2012). In small ponds, water temperature is the most influential variable governing direct evaporation from pond surfaces (Boyd, 1985). Additional evaporation losses can occur when ponds are aerated because aerators increase the area of contact between the water and the air by splashing water into the air, creating turbulence at the surface, or both. Evaporation is a cooling process, because heat must be added to water molecules to cause them to attain enough energy to escape the water surface.

Pumping water is a common practice in aquaculture to fill ponds, compensate for water loss by evaporation and seepage, and exchange water. The cost of pumping water varies according to several factors such as: volume of water discharge, pumping head, motor efficiency, and pump efficiency (Boyd and Tucker, 1998).

Water is scarce in many regions (Ahmed et al., 2000) and aquaculture competes with other water uses; therefore, there is a need to understand the relationship of aquaculture to local hydrology and water availability. This knowledge would be useful in developing recommendations for water conservation in aquaculture. Because little is known about the increase in evaporation caused by aeration, the present study was conducted to evaluate the influence of aeration on evaporation rate in ponds, determine the influence of evaporation on pond water temperature, and to compare the effect of daytime and nighttime aeration on pond evaporation and water temperature.

3.3. Materials and Methods

The experiment was performed at the Auburn University E. W. Shell Fisheries Center, Auburn, AL (USA) (32° 39'0 0.5" N, 85° 29'0 6.9" W). Six, 0.04-ha (0.1-acre) research earthen ponds located side by side, with the same dimensions and containing water inlet and outlet control structures were selected. The average depth of each pond is 0.85 m. The ponds have vertical concrete side walls that assure that water surface area is the same until water levels fall at least 30 cm below the top of the overflow structure. The study was conducted from early June to early October in 2013.

One pond had no aeration and was considered as a control (C) while the other five ponds were treated with nitrogen and phosphorus fertilizer twice per month at the rate of 9 kg N plus 9 kg P_2O_5/ha to promote phytoplankton blooms in aquaculture ponds. One of the five nutrient-enriched ponds had no aeration and was considered a nutrient-enriched control

(NEC), while the other four ponds were supplied with either one, two, three, or four 0.37-kW (0.5-hp) Air-O-Lator aerators (Air-O-Lator Corporation, Kansas City, Missouri, USA) (Figure 3.1). The Air-O-Lator is a vertical pump surface aerator that splashes water into the air. The aeration rates were 9.2, 18.4, 27.6 and 36.9 kW/ha. Ten grass carp (*Ctenopharyngodon idella*) were stocked into each pond for aquatic weed control, but no other species of fish were stocked.

The study was conducted in two phases. In the first phase, aerators were alternatively operated for 24 h (ON) and then turned off for 24 h (OFF). During the first phase, aerators were ON for 25 days and OFF for 25 days. In the second phase, aerators were alternatively operated for a period of 12 h during daytime (OnD) and turned off for a period of 12 h during nighttime (OffN) for 15 days. The operating schedule was then switched, and aerators were operated for a period of 12 h during nighttime (OnN), and turned off for a period of 12 h during daytime (OffD) for 15 days.

Water samples were collected once per day (first phase) and twice per day (second phase) from approximately 10 cm depth in each pond, placed in 0.5-L plastic bottles, and carried to the laboratory located within 300 m of the research ponds for immediate analysis. Turbidity was measured daily during the first phase, and twice a day during the second phase using a VWR Model 66120–200 turbidity meter (VWR International, Radnor, Pennsylvania, USA). Chlorophyll *a* (Chl *a*) concentration (membrane filtration, acetone extraction, and spectroscopy) was measured weekly as described by Boyd and Tucker (1992).

Water temperature at 70 cm depth in each study pond was monitored at 1-h intervals with a Model 64K HOBO Pendant® Temperature/Light Data Logger (UA-002-64, HOBOware®; Janesville, Wisconsin, USA). The logger was attached to the top surface of a brick using a Zip-Tie to assure that the sensor was pointing up. Each brick was suspended from both sides by 70-cm long ropes, and connected with a fishing net float at the other end.

This design ensured that the logger was mounted horizontally underwater with the sensor pointing directly towards the sky.

Surface water temperature in each pond and air temperature were monitored at 1-h intervals with Model 64K HOBO Pendant® Temperature/Alarm Data Loggers (UA-001-64, HOBOware®). The data loggers for monitoring surface water temperature were tied to the bottom surface of one of the two floats that suspended the brick. Two data loggers for monitoring air temperature were mounted at a height of 3 m under two open sheds ─ roof but no sides ─ located at about 200 m from the most distant pond. The data loggers were installed the day before starting the experiment and used until the end of the experiment. At the end of the study, software provided by the manufacturer (HOBOware Pro 3.7.1) was used to download data into a laptop computer. Data loggers were connected with the computer using HOBO Pendant Optic USB Base Station and Coupler (part # BASE-U-1).

A standard National Weather Service Class-A type evaporation pan (Forestry Supply, Jackson, Mississippi, USA) was used to measure evaporation. The pan was mounted on a level, wooden platform above a grassy surface. The pan was not in the shadow of trees, building or other tall objects, and weeds and grass around it were mowed regularly. The pan was filled to within 6 cm of the top with city water. Water loss to evaporation was measured by the aid of a stilling well and micrometer hook gauge. The pan was cleaned as necessary to keep it free from sediment, algae, and oil films that might alter the rate of evaporation. A standard rain gauge was installed on a level wooden platform over a grassy surface near the evaporation pan.

A stilling well consisting of a 10-cm diameter polyvinyl chloride pipe was installed in each pond close to the edge. A 1-cm hole was made in the side of the pipe to maintain the same water level in the pipe as in the pond. The water levels in the stilling wells also were measured with the micrometer hook gauge.

During the first phase, means of daily air and water temperatures were calculated by averaging all 1-h readings each day. Air temperatures were calculated as hourly average of temperature recorded by the two data loggers mounted in the sheds. The daily ranges of air and water temperatures were calculated as the difference between maximum and minimum temperature readings during the day. The daily temperature differential in each pond was determined as the difference between surface water temperature and water temperature at 70-cm depth. During the second phase, calculations were done for 12-h periods instead of daily calculations. The amount of water loss per kilowatt of aeration per hectare was calculated. The differences in turbidity between aeration periods when aerators were turned on and those when turned off were calculated. The cost that would have been accrued had the water been pumped into the ponds was calculated as described by Yoo and Boyd (1994).

3.3.1. Statistical analyses

Data were analyzed using means, standard deviations, t-tests, and simple linear regression. The Shapiro–Wilk test was utilized for normality analysis of the variables. Analysis of variance (ANOVA) was used in data with a normal distribution, and if there were significant differences, the Tukey's Studentized Range (HSD) test was used for post hoc analysis. Otherwise, the non-parametric Kruskal–Wallis test was used for data not normally distributed, and Wilcoxon signed ranks test was used to calculate the difference between samples in cases showing differences with the Kruskal–Wallis test. Statistical significance was set at $P < 0.05$, and all data were presented as the mean ± standard error (*SE*). For conducting t-tests, the protocol for calculating the t-value took into account whether variances were homogeneous as outlined by Steel and Torrie (1980). Analyses were performed with SAS® version 9.4 statistical software (SAS Institute Inc., Cary, North Carolina, USA).

3.3.2. Calculations of evaporation during the first phase

The water-level change in a pond or a class-A evaporation pan was measured daily:

$$\Delta \text{ Pond or } \Delta \text{ Pan} = WL_2 - (WL_1 + P)$$

where Δ Pond or Δ Pan = change in water level during a 24 h period (mm/day); WL_1 = initial water level (mm); WL_2 = water level after 24 h (mm); P = rainfall during 24 h period (mm).

Pond evaporation was measured as:

$$E_{off} = \Delta \text{ Pan}_{off} \text{ x monthly pan coefficient}$$

$$E_{on} = \Delta \text{ Pan}_{on} \text{ x monthly pan coefficient}$$

where E_{off} = estimated pond evaporation during aeration OFF period (mm/day); E_{on} = estimated pond evaporation during aeration ON period (mm/day); $\Delta \text{ Pan}_{off}$ = water-level change during OFF period (mm/day); $\Delta \text{ Pan}_{on}$ = water-level change during ON period (mm/day); monthly pan coefficient as estimated by (Boyd, 1985).

Pond seepage was calculated as:

$$S = \Delta \text{ Pond}_{off} - E_{off}$$

where S = pond seepage during 24 h (mm/day); $\Delta \text{ Pond}_{off}$ = change in water level during OFF period (mm/day).

Total pond evaporation was estimated as shown below:

$$TE = \Delta \text{ Pond}_{on} - S$$

where TE = total pond evaporation during ON period (mm/day).

Evaporation caused by aeration, as estimated from water-level changes, was determined by the following equations:

$$EA_{WL(pan)} = TE - E_{on}$$

where $EA_{WL(pan)}$ = evaporation caused by aeration for 24 h (mm/day). It was estimated from water-level change in the pond. In this method of estimation, seepage was calculated based on $\Delta\ Pan_{off}$.

$$EA_{WL(on\text{-}off)} = \Delta\ Pond_{on} - \Delta\ Pond_{off}$$

where $EA_{WL(on\text{-}off)}$ = evaporation caused by aeration for 24 h (mm/day). In this method of estimation, seepage was considered to be constant during ON and OFF periods.

Evaporation caused by aeration as estimated based on heat loss from a water body was determined with the following equation:

$$EA_t = (D)\ (T_1 - T_2)\ /\ [540 + (100 - T_1)]$$

where EA_t = evaporation caused by aeration for 24 h (mm/day); D = pond's average depth (mm); T_1 = average water temperature [(surface water temperature + water temperature at 70 cm depth) / 2] of NEC pond (°C); T_2 = average water temperature of aerated pond (°C); 540 = latent heat of vaporization of water is 540 calories/g.

3.3.3. Calculations of evaporation caused by aeration during second phase

The equations above also were used to calculate evaporation caused by aeration during 12-h periods.

3.3.4. Calculation of pumping cost

The cost of pumping water to compensate water loss caused by aeration was determined with the following equation as described by Yoo and Boyd (1994):

$$PC = QHSET\ /\ 0.102\ e_p\ e_m$$

where PC = pumping cost ($); Q = discharge ($m^3/s$); H = pumping head (m); S = specific gravity (S = 1 for water); e_p = pump efficiency; e_m = motor efficiency; E = cost of electricity ($/kW.h); T = pumping time (h).

3.4. Results and Discussion

During both phases of the study, rainfall was sufficient to maintain water levels enough to maintain a constant pond water surface area. Water levels were never great enough to cause overflow, and water loss from ponds resulted solely from evaporation and seepage.

During the first phase, average daily air temperature and pan evaporation were calculated separately for ON and OFF (Table **3.1**). There was no difference between ON and OFF periods for average daily air temperature ($t = - 0.05$, $p = 0.9639$) and pan evaporation ($t = - 0.55$, $p = 0.5816$). Weather conditions obviously differed from day to day between ON and OFF periods, but over 50-day period differences in air temperature and pan evaporation did not result between ON and OFF days.

During the second phase, there was also no difference between average air temperature between ON and OFF periods (Table **3.1**) whether ON was during the day ($t = -1.55$, $p = 0.1327$) or night ($t = -0.19$, $p = 0.8471$). Moreover, there was no difference in average pan evaporation during daytime between days when aerators were on and those when aerators were off ($t = 0.24$, $p = 0.8120$). However, the average value of pan evaporation during OffN was higher than that during OnN ($t = 2.51$, $p = 0.0191$). This apparently was related to the particular weather patterns during the study and not related to aeration.

3.4.1. Water temperature

Means of differences in water temperature over a 24-hr period between each pond and the NEC pond during the ON period were calculated (Figure 3.2-a). Both surface water temperature ($\chi^2 = 1512.49$, $p < 0.0001$) and water temperature at 70-cm depth ($\chi^2 = 1669.84$, $p < 0.0001$) were different for ponds with different numbers of Air-O-Lator units. The mean ± *SE* for the decrease in the surface water temperature caused by having this aerator on for 24 h was 0.92°C ± 0.09 for an aeration rate of 9.2 kW/ha and 2.84°C ± 0.13 for 36.9 kW/ha of aeration. The mean ± *SE* of this decrease in the deep water temperature was 1.26°C ± 0.07 for an aeration rate of 9.2 kW/ha and 3.42°C ± 0.16 for 36.9 kW/ha of aeration. The regression between aeration rate (kW/ha) and decrease in surface water temperature had an R^2 of 0.517, while the regression between aeration rate (kW/ha) and decrease in water temperature at 70-cm depth had an R^2 of 0.605 (Figure 3.3). There was a clear effect of increasing the number of Air-O-Lator units on decreasing either the surface or bottom water temperature. In all aerated ponds, the decrease in water temperature at 70-cm depth was greater than that at the surface ($t = 2.85$, $p = 0.0047$).

The means ± *SE* for surface water temperature and water temperature at 70 cm depth of all ponds were determined during OnD and OnN periods (Table 3.2). During OnD, in all aerated ponds and C pond, there were no differences between surface and deep water temperatures in the same pond. However, in NEC pond, mean deep water temperature was significantly higher than mean surface water temperature during daytime ($t = 8.19$, $p < 0.0001$). During OnN, in the pond with four aerators, mean deep water temperature was significantly lower than mean surface water temperature ($t = -2.35$, $p = 0.0195$).

Shallow aquaculture ponds stratify thermally during daytime and destratify during nighttime. Similarly, the NEC pond – not aerated- was stratified thermally during daytime with deep water warmer than surface water, but it destratified during nighttime. Mechanical surface aeration resulted in destratification of aerated ponds during daytime. Higher rates of aeration, especially during nighttime aeration, resulted in cooler water at 70 cm depth than surface water.

During both OnD ($\chi^2 = 301.09$, $p < 0.0001$) and OnN ($\chi^2 = 396.61$, $p < 0.0001$), means of surface water temperatures were different among ponds with different numbers of aerators and control ponds. Means of water temperature at 70 cm depth were also different among ponds with different numbers of aerators and control ponds during OnD ($\chi^2 = 391.24$, $p < 0.0001$) and OnN ($\chi^2 = 408.61$, $p < 0.0001$).

During OnD, all aerated ponds –even the pond with one aerator– had cooler water at 70-cm depth than those in control ponds (Table 3.2). During both OnD and OnN periods, there were no differences in temperatures between surface and water at 70 cm depth in the pond with two aerators and the one with three aerators. Furthermore, the lowest temperature at the surface and at 70-cm depth was in the pond with four aerators. The greater the aeration rate during either day or night, the cooler were water at surface and 70-cm depth. During OnD, surface water in the NEC pond was cooler than that of the control pond, while there was no difference between water temperatures at 70 cm in these ponds. However, during OnN, both surface and 70-cm water temperatures were cooler in the NEC pond than that in the C pond.

Means of differences in water temperatures at the water surface and at 70 cm depth in each aerated pond and in the NEC pond were calculated for OnD and OnN periods (Figure 3.2-b). The means ± *SE* for the decrease in the surface water temperature caused by having the aerator on for 12 h during day or for 12 h during nighttime were 0.23°C ± 0.04 and 0.64°C ± 0.04, respectively, for an aeration rate of 9.2 kW/ha. The decreases in temperature were 2.02°C ± 0.05 and 2.53°C ± 0.06, respectively, for 36.9 kW/ha of aeration. The means ± *SE* of the decrease in temperature at 70 cm during day as compared to the nighttime were 1.60°C ± 0.08 and 0.73°C ± 0.04, respectively, for an aeration rate of 9.2 kW/ha, and 3.75°C ± 0.09 and 2.92°C ± 0.06, respectively, for 36.9 kW/ha of aeration.

All aerated ponds had lower temperatures during day and night and at the surface and at 70 cm depth than did the NEC pond. Greater temperature decreases were recorded in ponds with higher aeration rates. In all aerated ponds, the decrease in surface water temperature was greater during OnN, while the decrease in temperature at 70 cm depth was greater during OnD (Figure 3.2-b).

Increased aeration rate lowers water temperature, an effect that can be positive or negative depending on a farm's location, the season, and the farmed species. The production potential would be impaired when the water temperature falls outside the optimum range for significant periods (Wickins and Lee, 2008). Thus, during high temperature, aeration could benefit production by lowering temperature toward the optimum range. On the other hand, when temperature is low, aeration could lower production.

High NH_3-N values were recorded during summer when the water temperature was elevated (Ahmed and Abdelrahman, 2011). One of the positive consequences of lowering water temperature is to moderate NH_3-N concentration. A 1°C decrease in temperature in a water containing 1 mg/L total ammonia-nitrogen at pH 8.0 will decrease the NH_3-N concentration by 0.004 mg L^{-1} (Zhou and Boyd, 2015). Also, rates of respiration and photosynthesis are affected by water temperature (Tucker, 2005).

3.4.2. Evaporation rate

While aerators were on for 24 h, the total evaporation loss consisted of pond evaporation and evaporation caused by aeration. There were no differences in total evaporation between ponds with one Air-O-Lator, NEC, and C ponds (Table **3.3**). Total evaporation of the pond with two Air-O-Lator units was not different from that of the NEC pond, while total evaporation rates of ponds with three and four Air-O-Lator units were greater than that of the control ponds ($\chi^2 = 30.29$, $p < 0.0001$). Thus, increasing aeration rate resulted in greater total pond evaporation.

Pond evaporation caused by aeration with the Air-O-Lator units for 24 h was determined (Figure 3.4) by three different methods. The $EA_{WL(pan)}$ and $EA_{WL(on\text{-}off)}$ methods for calculating evaporation rate were based on water level measurements, while the EA_t measurement was based on heat loss from the water body. For each aerated pond, there were no differences among the results of the three estimation methods ($\chi^2 = 1.09$, $p = 0.5810$).

Using $EA_{WL(pan)}$ and $EA_{WL(on\text{-}off)}$, the only difference was between ponds for one aerator as compared to four aerators ($\chi^2 = 11.69$, $p = 0.0085$) and ($\chi^2 = 13.39$, $p = 0.0039$), respectively. While with EA_t, ponds with two and three aerators were not different, but all other ponds were differed ($\chi^2 = 60.93$, $p < 0.0001$).

Estimation of pond evaporation caused by aeration based on heat loss from ponds provided stronger evidence of differences between ponds with different aeration rates. This may be because the EA_t estimation was based on the difference in the average water temperature between each aerated pond and the NEC pond; while $EA_{WL(pan)}$ and $EA_{WL(on\text{-}off)}$ were based on one reading of the water level per day. During the first phase of the study, 48 daily readings of temperature were made in each pond, while only one water level reading was performed. More readings would likely have resulted in better estimates. Other possible reasons are differences in seepage during the ON and OFF periods ($EA_{WL(pan)}$ and $EA_{WL(on\text{-}off)}$) or use of the same estimated pond evaporation for all ponds ($EA_{WL(pan)}$).

During the second phase in which aerators were operated 12-h, changes in the water level (Δ Pond) during the 12-h period (mm/12 h) were calculated (Figure 3.5). During OffD and OffN periods, Δ Pond consisted of pond seepage plus pond evaporation, and there was no difference in water loss from NEC pond during OffD and that during OffN. While in all other ponds, water losses during OffN were greater than during OffD (Figure 3.5-d). The pattern changed when the aerators were on; ponds with higher aeration rates showed less water loss during nighttime than that during daytime (Figure 3.5-c). During OnD, Δ Pond consisted of pond seepage, pond evaporation, and evaporation caused by aeration. Thus, in all aerated ponds, water losses during OnD were higher than during OffD (Figure 3.5-a). During OnN, evaporation caused by aeration was subtracting from pond water loss during OffN. The higher the aeration rates, the less the water loss was during OnN than during offN (Figure 3.5-b).

No differences in total evaporation from the NEC and C ponds occurred during OnD, and OnN (Figure 3.6). The means for total evaporation while aerators were on for 12 h during day and nighttime were 3.78 and 1.86 mm, respectively, for an aeration rate of 9.2 kW/ha, and 4.63 and 0.81 mm, respectively, for 18.40 kW/ha of aeration. Evaporation caused by aeration was greater with a higher aeration rate during daytime, while evaporation decreased during nighttime (Figure 3.7-a and Figure 3.7-b). Increasing the rate of aeration, caused TE, $EA_{WL(pan)}$ and $EA_{WL(on-off)}$ to increase during daytime, while it decreased during nighttime. Therefore, there is diurnal variation in how evaporation responded to increasing aeration rate.

EA_t was calculated based on the difference in average water temperature between aerated ponds and the NEC pond, and this difference increased with greater aeration rate either during daylight or nighttime (Figure 3.2). Therefore, EA_t increased with greater aeration rate during both OnD and OnN (Figure 3.7-c). During OnN, greater aeration rates increased EA_t but decreased Δ Pond, TE, $EA_{WL(pan)}$ and $EA_{WL(on-off)}$ (Figure 3.5, Figure 3.6, Figure 3.7-a and Figure 3.7-b, respectively).

Aeration rates in earthen-lined ponds range from 5 kW/ha to 30 kW/ha, and even greater rates may sometimes be used in plastic-lined ponds for biofloc-technology (Boyd and Tucker, 2014). Water losses (m^3/ha/d) caused by different aeration rates were calculated based on heat loss from all aerated ponds (Table 3.4). The evaporation loss increased linearly with greater amount of aeration, with R^2 of 0.969 (Figure 3.8). The regression equation was $\hat{y} = 7.0866 + 0.967x$. Evaporation rate increased 32 and 92% when ponds were aerated for 24 h with one and four Air-O-Lator aerators, respectively (Table 3.4).

The costs of well water pumping to compensate the water loss caused by continuous aeration for 100 days were \$3.2 /ha and \$9.3 /ha for the aeration rates of 9.2 kW/ha and 36.9 kW/ha, respectively, assuming 5 m pumping head (Table 3.4). This cost increased linearly with greater aeration rates, with R^2 of 0.969 (Figure 3.9). Of course, cost also would be higher when pumping head is greater (Figure 3.9). Commercial ponds usually are aerated with larger aeration units than used in this research. Oxygen transfer rates for surface aerators increase with the amount of water splashed into the air (Boyd, 1998; Boyd and Tucker, 1998). Larger aerators have oxygen-transfer rates about twice those of the units used in this study (Boyd and Ahmad, 1987). Thus, in commercial aquaculture, the water loss per unit of aeration is likely greater than reported here.

Water loss caused by aeration will increase water use in aquaculture ponds—especially in arid regions. Some farmers aerate ponds at times when dissolved oxygen concentrations are adequate. This practice increases both energy consumption and evaporation and should be discouraged in favor of operating aerators only during periods when dissolved oxygen concentration is low. This could be accomplished by using automated systems for turning aerators on and off in response to dissolved oxygen concentration (Boyd and Tucker, 2014). Aeration is highly beneficial (Boyd and Tucker, 1998) and its benefit for increasing fish production greatly exceed the pumping cost to replenish water loss to greater evaporation.

3.4.3. Water turbidity

Differences in turbidity between ON and OFF periods were calculated. In the first phase, there was no difference in turbidity between the ON and OFF periods (t = -0.15, p = 0.8822). In addition, the increase in turbidity during ON days than that in OFF days was not different among ponds with different numbers of Air-O-Lator units and the control ponds (F = 0.22, p = 0.9521). In the second phase, there was no difference in turbidity between OnD, OnN, OffD, and OffN (F = 0.32, p = 0.8094). Thus, Air-O-Lator units used in this study do not increase water turbidity significantly. Of course, this observation may not apply to other types of aerators.

During the study, the means ± *SE* for turbidity of the C and NEC ponds were 0.99 NTU ± 0.04 and 2.21 NTU ± 0.18, respectively. The NEC pond was more turbid than the C pond ($t = 6.5$, $p < 0.0001$). Mean ± *SE* chlorophyll *a* of the pond C and the NEC pond were 3.49 µg L^{-1} ± 0.32 and 14.79 µg L^{-1} ± 1.11 respectively ($t = 9.8$, $p < 0.0001$). Fertilization resulted in the increased turbidity. Evaporation caused by the turbidity increase was calculated based on the temperature difference between the NEC and C ponds. Evaporation rates in the NEC pond were more than those in the C pond by 1.34 ± 0.09 mm/12 h during daytime and 1.25 ± 0.10 at night. Greater turbidity as a result of fertilization did not increase evaporation between daytime and nighttime.

3.5. Conclusions

Increased aeration rate lowers water temperature and increases the evaporation rate. Aeration during nighttime causes decrease in surface temperature greater than the bottom, while aeration during daylight causes decrease in temperature of water at 70-cm depth greater than the surface. Water loss caused by aeration is higher during daylight. A nutrient-enriched pond evaporates more than that of unfertilized pond. Air-O-Lator units do not increase water turbidity. Economic benefits from reduced pumping costs may be obtained by restricting aeration to periods of need, particularly in regions where the water is scarce. There are many kinds of aerators and commercial ponds are usually aerated with larger units than used in this research; therefore, further work is required to study the water loss caused by different aerator types.

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Table 3.1 Means and standard errors for average air temperature (°C), and class-A pan evaporation (mm). Values were calculated during the first phase for ON (aerators on for 24 h), OFF (aerators off for 24 h), and during the second phase for OnD (aerators on for 12 h daytime), OffD (aerators off for 12 h daytime), OnN (aerators on for 12 h nighttime), and OffN (aerators off for 12 h nighttime) periods.

Parameter	24 h				Daytime				Nighttime			
	ON	OFF	*t*-value	*p*-value	OnD	OffD	*t*-value	*p*-value	OnN	OffN	*t*-value	*p*-value
Air Temperature	25.95 ± 0.29	25.92 ± 0.40	-0.05	0.964	30.82 ± 0.67	29.34 ± 0.67	-1.55	0.133	22.63 ± 0.47	22.50 ± 0.49	-0.2	0.847
Pan evaporation*	5.86 ± 0.51	5.42 ± 0.59	-0.55	0.582	3.71 ± 0.28	3.81 ± 0.32	0.24	0.812	0.95 ± 0.20	1.85 ± 0.30	2.48	0.020

* The unit of pan evaporation is mm/d for ON and OFF, while it is mm/12h for OnD, OffD, OnN, and OffN.

Table 3.2 Means and standard errors for hourly surface water temperature (°C), and water temperature at 70-cm depth in nutrient-enriched control (NEC) pond, control (C) pond, and ponds that were aerated with Air-O-Lator units at different aeration rate. Values were calculated during the second phase for OnD (aerators on for 12 h daytime), and OnN (aerators on for 12 h nighttime).

Pond	OnD				OnN			
	Surface	70-cm depth	*t*-value	*p*-value	Surface	70-cm depth	*t*-value	*p*-value
C	31.17 ± 0.14 ^{a}	31.24 ± 0.15 ^{a}	0.34	0.7332	30.18 ± 0.11 ^{a}	29.95 ± 0.12 ^{a}	-1.36	0.1738
NEC	29.40 ± 0.13 ^{b}	31.09 ± 0.16 ^{a}	8.19	< 0.0001*	29.17 ± 0.10 ^{b}	29.15 ± 0.10 ^{b}	-0.16	0.8694
1 aerator	29.17 ± 0.15 ^{b}	29.49 ± 0.14 ^{b}	1.55	0.1224	28.54 ± 0.12 ^{c}	28.42 ± 0.12 ^{c}	-0.69	0.4883
2 aerators	28.39 ± 0.14 ^{c}	28.42 ± 0.13 ^{c}	0.18	0.8541	27.60 ± 0.12 ^{d}	27.48 ± 0.12 ^{d}	-0.78	0.4366
3 aerators	28.31 ± 0.14 ^{c}	28.27 ± 0.14 ^{c}	-0.21	0.8369	27.47 ± 0.12 ^{d}	27.27 ± 0.12 ^{d}	-1.19	0.2353
4 aerators	27.38 ± 0.13 ^{d}	27.34 ± 0.14 ^{d}	-0.17	0.8644	26.65 ± 0.12 ^{e}	26.23 ± 0.13 ^{e}	-2.35	0.0195*

Means in the same column with the same letter are not significantly different.

Table 3.3 Means and standard errors (*SE*) for total pond evaporation in nutrient-enriched control (NEC) pond, control (C) pond, and ponds that were aerated with Air-O-Lator units at different aeration rate. (Means were tested by Tukey's Studentized Range (HSD) test; entries indicated by the same letter in a column do not differ at $p < 0.05$.

Pond	Aeration rate (kW/ha)	Total evaporation Mean (mm/d) ± *SE*
C	0	$4.38 \pm 0.58\ ^{d}$
NEC	0	$4.52 \pm 0.45\ ^{cd}$
1 aerator	9.2	$5.43 \pm 0.62\ ^{bcd}$
2 aerators	18.4	$6.98 \pm 0.63\ ^{abc}$
3 aerators	27.6	$7.60 \pm 0.65\ ^{ab}$
4 aerators	36.9	$8.29 \pm 0.69\ ^{a}$

Table 3.4 Evaporation caused by aeration (mm/d) for 24 h by different aeration rates (kW/ha), volume of water loss caused by aeration (m^3/ha/d), percentage of the increase in evaporation caused by aeration (%), and the well water pumping cost ($/ha) to compensate the water loss caused by aeration for 24 h.

Parameter	Unit	Aeration rate (kW/ha)	Aeration for 24 h
Mean ± *SE* [a]	mm/d	9.2	1.52 ± 0.10
		18.4	2.73 ± 0.15
		27.6	3.14 ± 0.17
		36.9	4.35 ± 0.22
Volume of water loss	m^3/ha/d	9.2	15.18
		18.4	27.27
		27.6	31.41
		36.9	43.55
Increase of evaporation [b]	%	9.2	32.01
		18.4	57.49
		27.6	66.21
		36.9	91.82
Well water pumping cost [c]	$/ha	9.2	0.03
		18.4	0.06
		27.6	0.07
		36.9	0.09

[a] Mean ± *SE* for evaporation caused by aeration (EA_t).

[b] Percentage of increase in evaporation as a result of aeration for 24 h was calculated as compared to pond evaporation (pan evaporation X pan coefficient) during ON period.

[c] Well water pumping cost was estimated assuming electricity cost is 0.1 $/kWh, discharge is 0.032 m^3/s (500 gpm), pumping head is 5 m, pump efficiency is 0.80, and motor efficiency is 0.80.

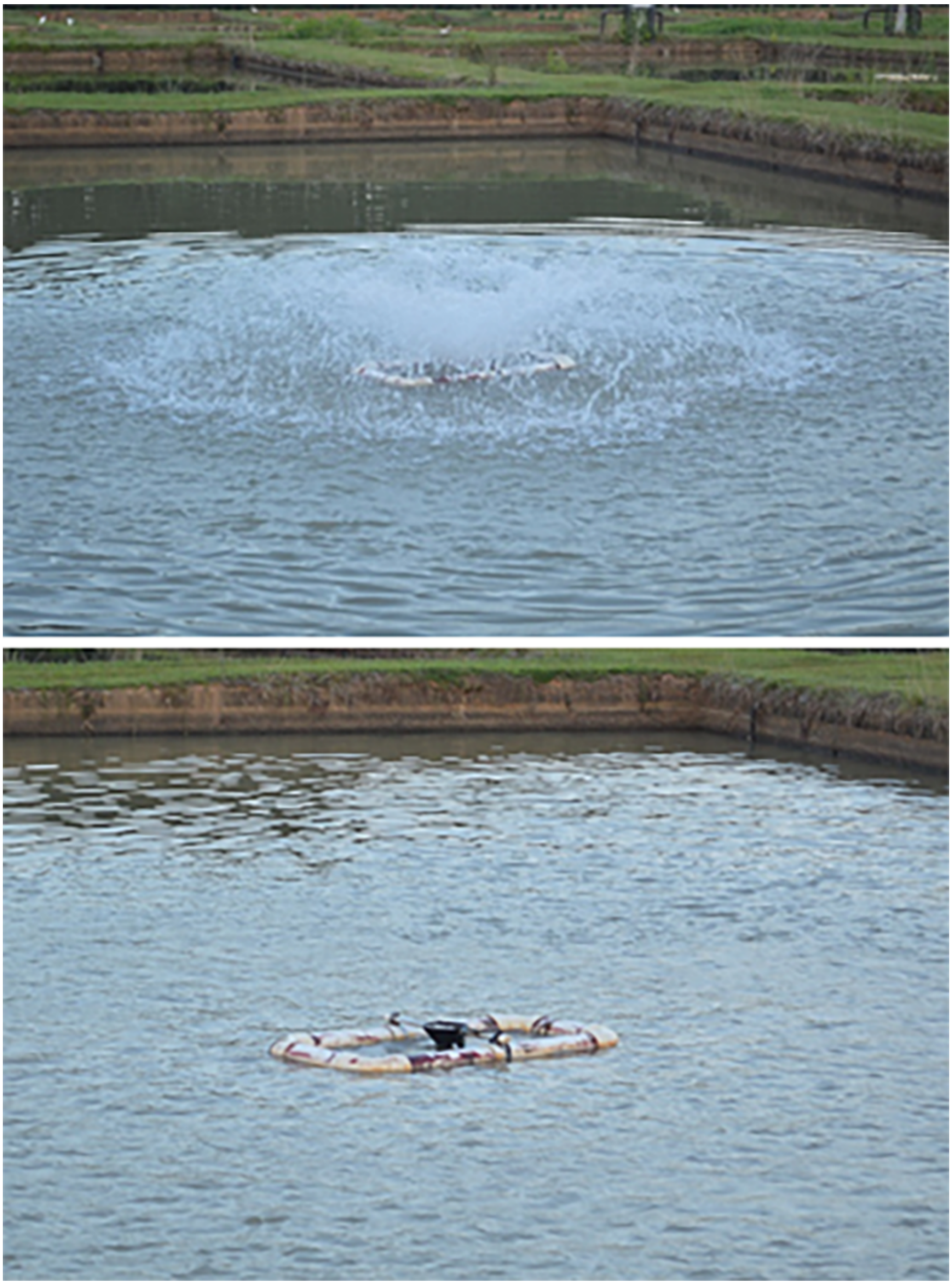

Figure 3.1 A 0.37-kW Air-O-lator aerator while it was turned on (upper picture), and turned off (lower picture).

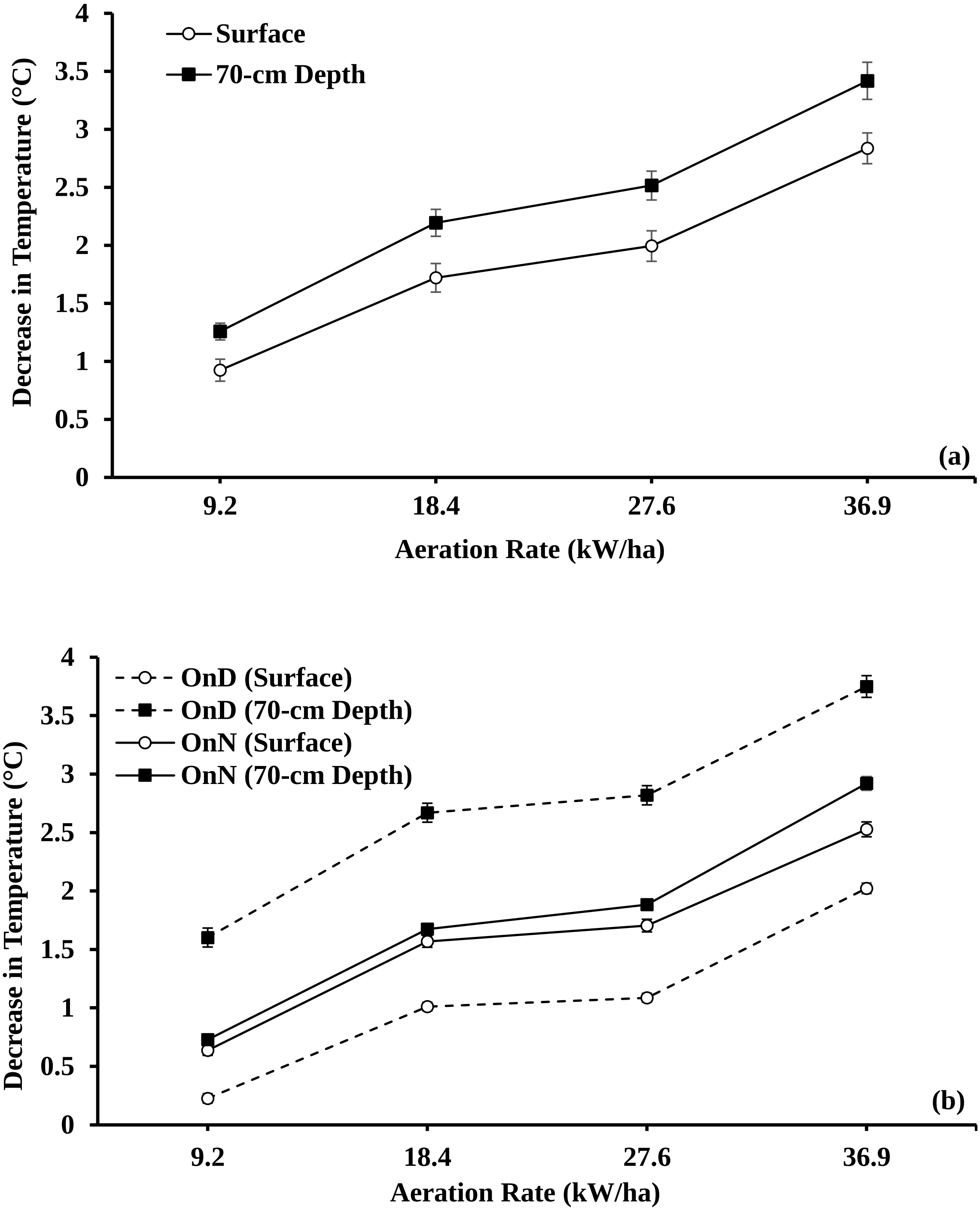

Figure 3.2 Means and standard errors for differences in water temperature between aerated ponds and the nutrient-enriched control pond when aerators were operated (a) continuously for 24 h; (b) either during daytime (OnD) or nighttime (OnN).

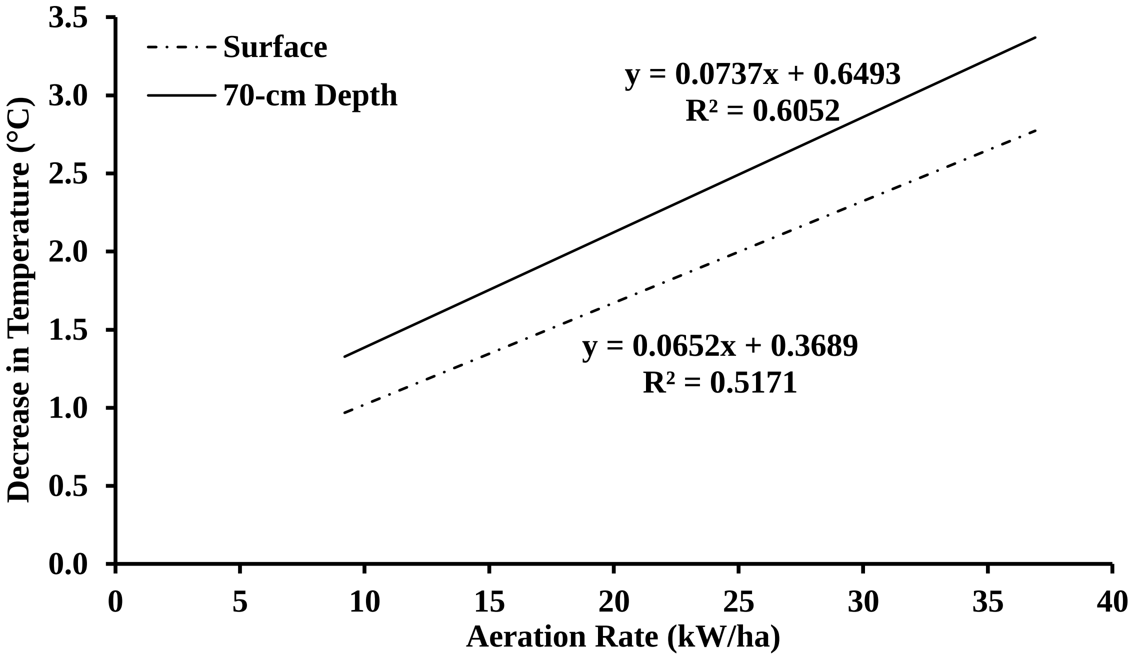

Figure 3.3 Relationships between the difference in average daily water temperature at the surface and 70-cm depth in aerated ponds and the nutrient-enriched control pond when aerators were operated continuously for 24 h.

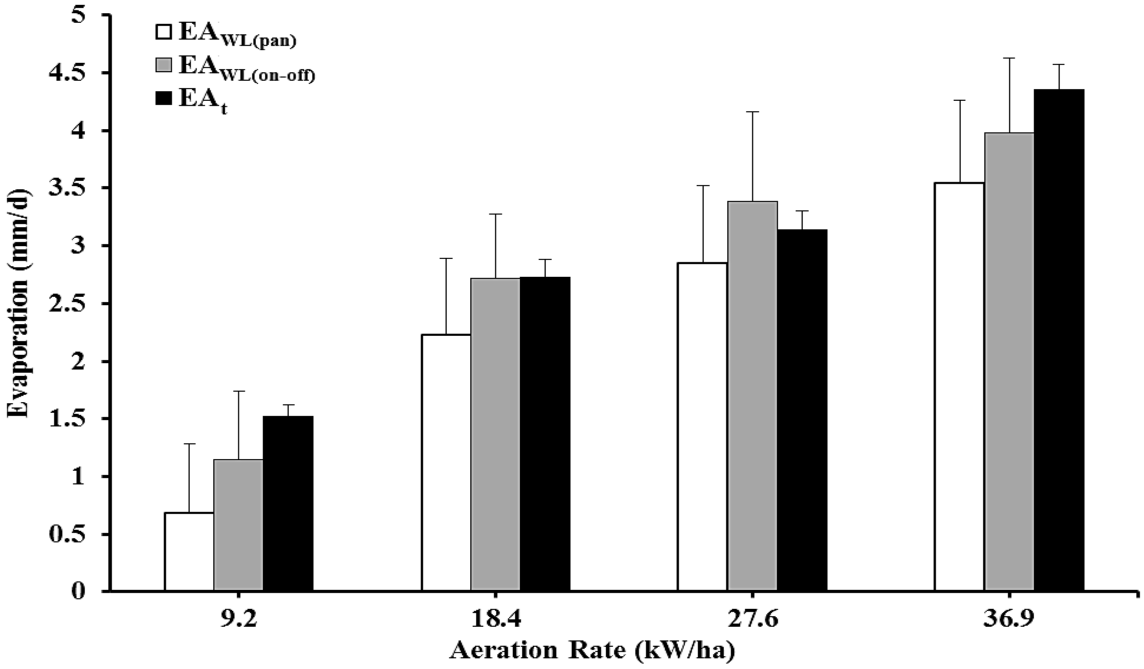

Figure 3.4 Means and standard errors for pond evaporation caused by different aeration rates for 24 h. These values were calculated by three different methods. The EA$_{WL(pan)}$ and EA$_{Wl(on-off)}$ values were based on water level measurement while EA$_t$ value was based on heat loss from the water body.

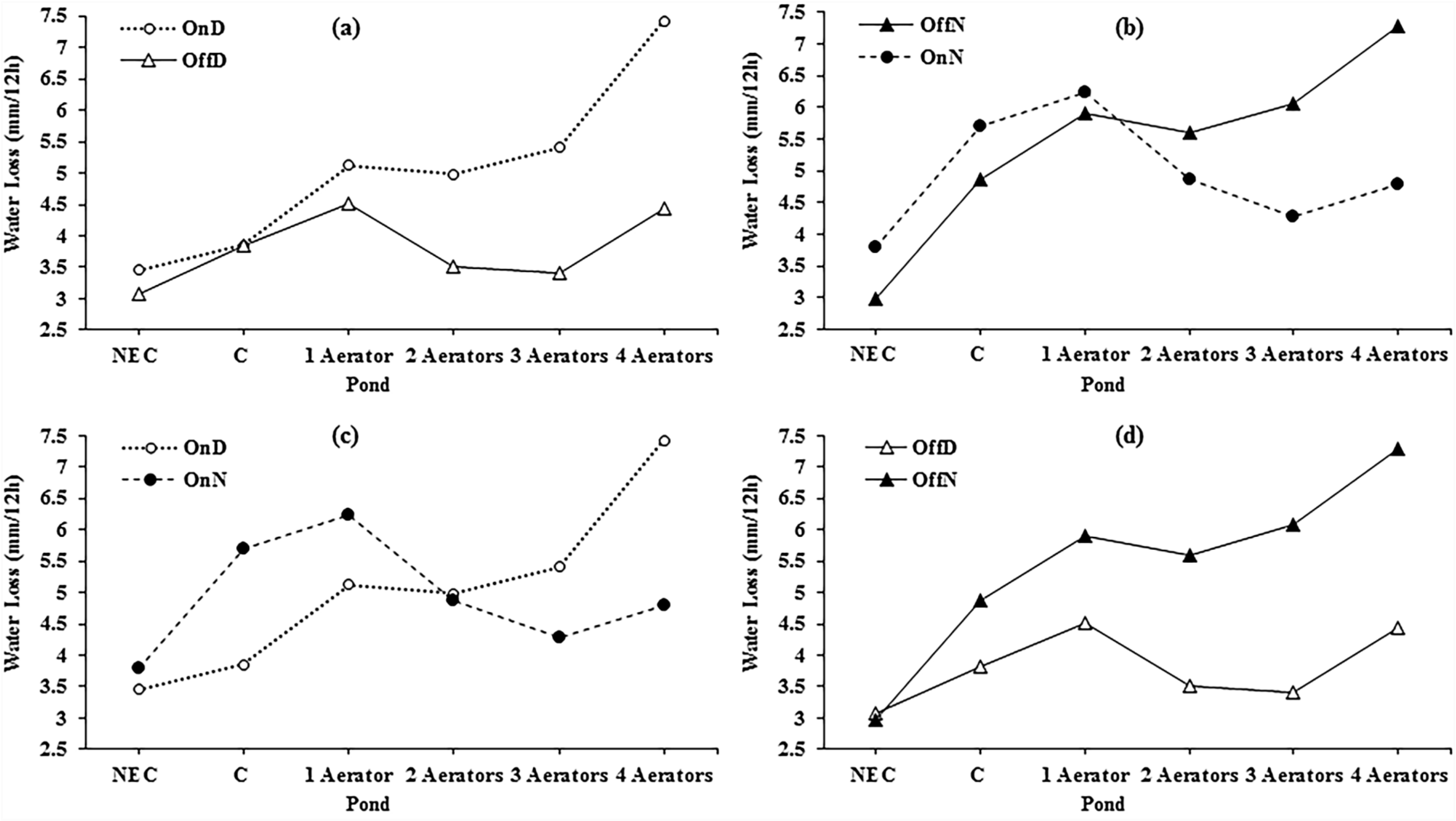

Figure 3.5 Means for water loss (Δ Pond) in the control pond (C), the nutrient-enriched control pond (NEC), and from ponds with different numbers of 0.37-kW Air-O-Lator units (1, 2, 3 and 4) while aerators were either turned on for 12 h during daytime (OnD) and off during nighttime (OffN); or turned off for 12 h during daytime (OffD), and on during nighttime (OnN).

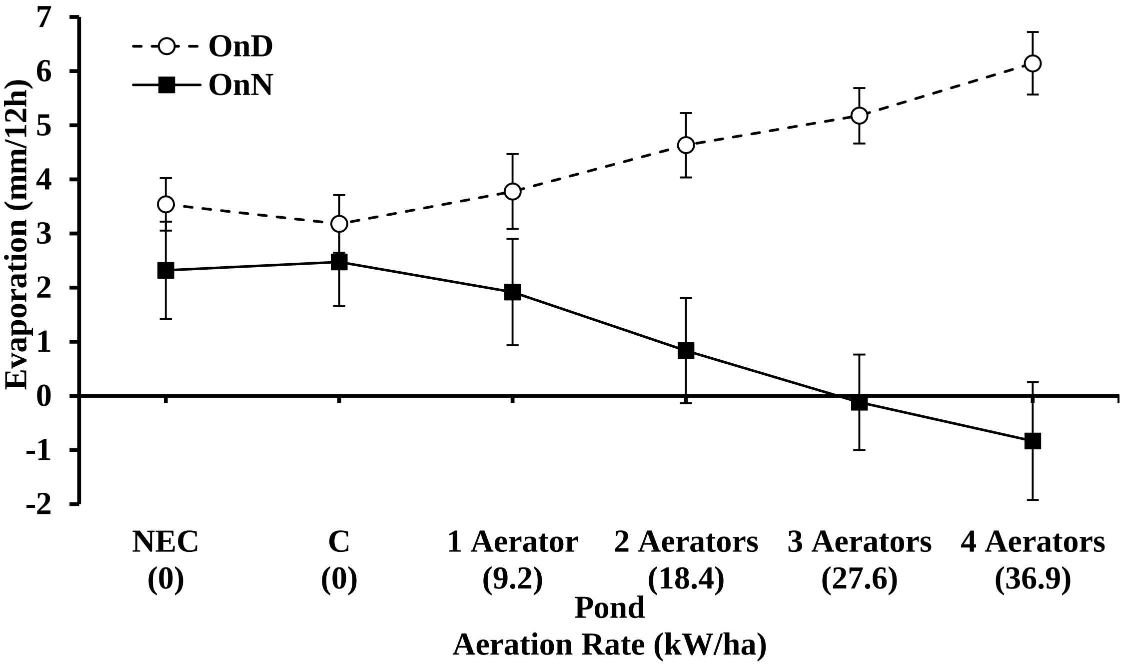

Figure 3.6 Means and standard errors for total evaporation (TE) in the control pond (C), the nutrient-enriched control pond (NEC), each aerated pond while different numbers of 0.37-kW Air-O-Lator units (1, 2, 3 and 4) were on for 12 h during day light (OnD) and during nighttime (OnN).

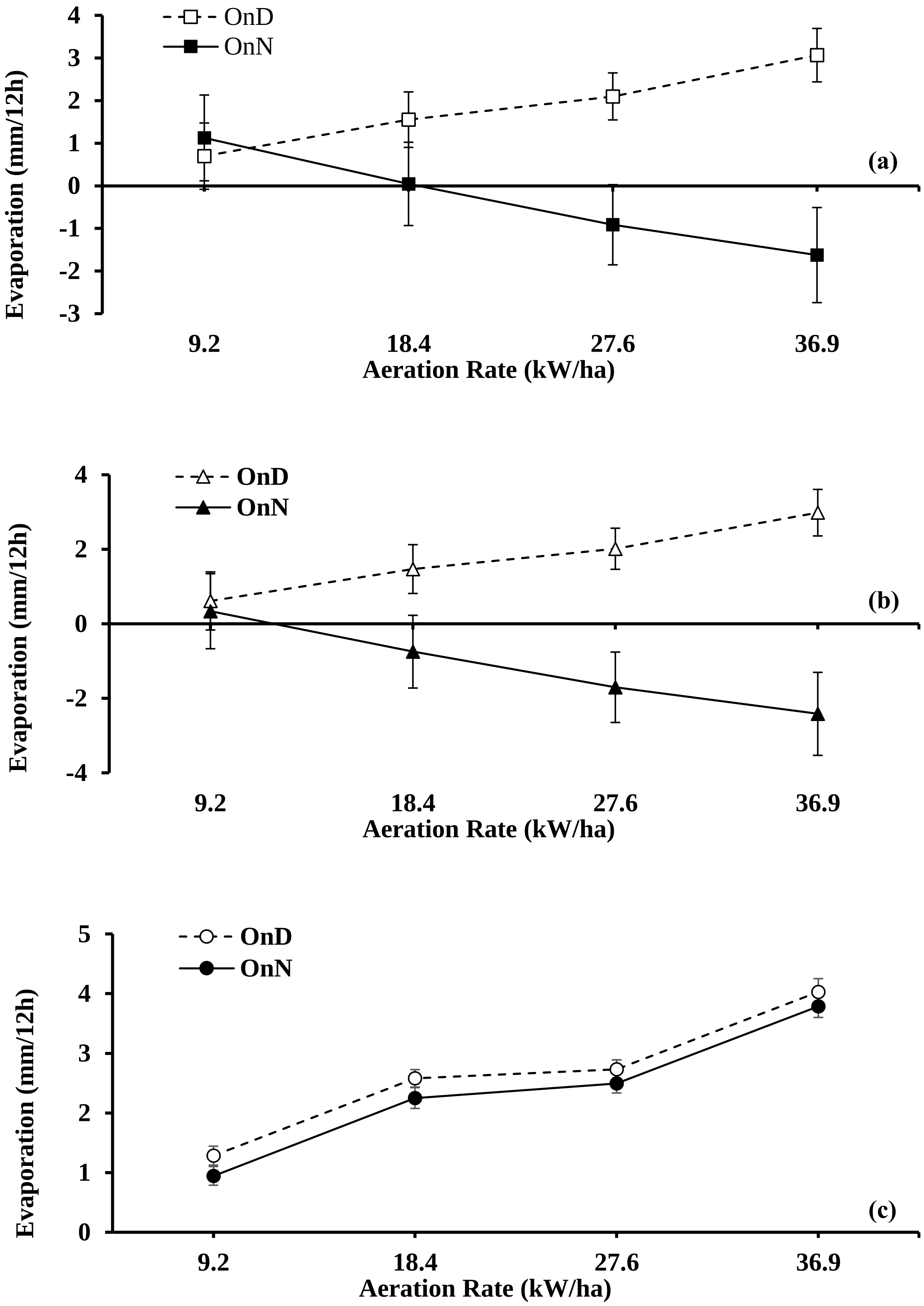

Figure 3.7 Means and standard errors for pond evaporation caused by different aeration rates while aerators were turned on for 12 h either during daytime (OnD) or during nighttime (OnN). These values were calculated by three different methods. The EA_{WL}(pan) (a) and EA_{WL}(on-off) (b) values were based on water level measurement while EAt value (c) was based on heat loss from the water body.

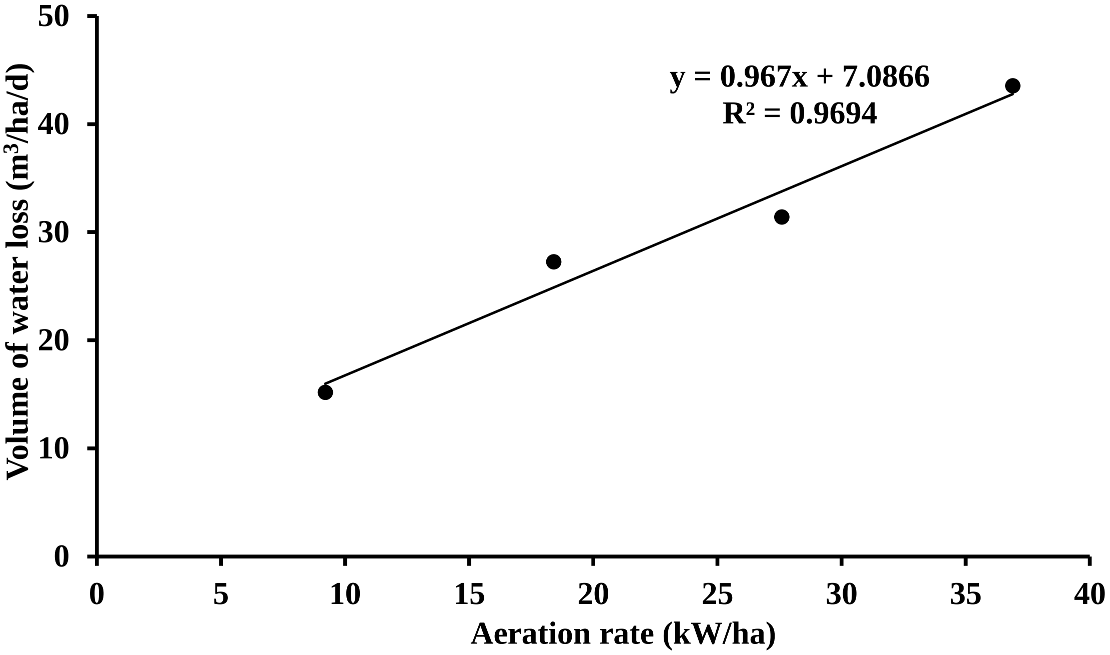

Figure 3.8 Relationship between the aeration rate (kW/ha) and the mean volume of water loss (m^3/ha/d) caused by aeration using 0.37-kW Air-O-Lator units for 24 h.

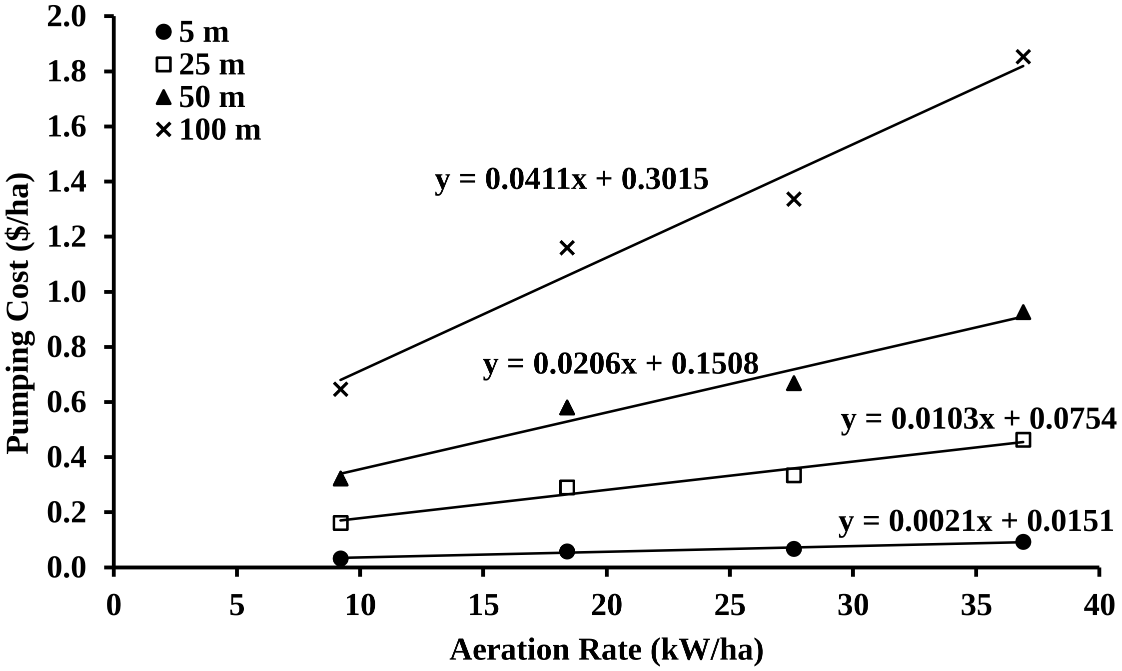

Figure 3.9 Relationships between the aeration rate (kW/ha) and the water pumping cost ($/ha) to compensate the water loss caused by aeration using 0.37-kW Air-O-Lator units for 24 h ($R^2 = 0.9694$). These values were calculated at pumping heads of 5, 25, 50, and 100 m.

Chapter 4 Influence of Variation in Water Temperature on Survival, Growth, and Yield of Pacific White Shrimp *Litopenaeus vannamei* in Inland Ponds for Low-Salinity Culture

4.1. Abstract

There is considerable interest in the culture of whiteleg shrimp (*Litopenaeus vannamei*) in inland low-salinity water in Alabama and other states in the Sunbelt region of the US. However, the growing season is truncated as compared to tropical or subtropical areas where this species is typically cultured, and temperature is thought to be a major factor influencing shrimp production in the US. This study, conducted at Greene Prairie Aquafarm located in west-central Alabama, considered water temperature patterns on a shrimp farm in different ponds and different years; and sought possible effects of bottom water temperature in ponds on variation in shrimp survival, growth and production. Water temperature at 1.2 m depth in 22 ponds and air temperature were monitored at 1-h intervals during the 2012, 2013, 2014 and 2015 growing seasons. Records of stocking rates, survival rates, and production were provided by the farm owner. Correlation analysis and linear mixed model analysis of variance were used. Results showed that the hourly water temperatures were different among ponds. The range of water temperature in each pond explained 41% of the variance in average final weight of shrimp harvested from each pond. In conclusion, results suggest that variation in water temperature patterns has considerable influence on shrimp growth and survival in ponds.

Keywords: Water quality, water temperature, low-salinity, inland shrimp culture *Litopenaeus vannamei*, shrimp production

4.2. Introduction

Shrimp farming expanded greatly during the 1980s and now is a multi-billion dollar a year industry (Moss et al., 2006). Although penaeid shrimp naturally inhabit marine environments, some of them, such as the whiteleg shrimp, *Litopenaeus vannamei*, are not only able to tolerate exposure to low salinity but also to survive and grow well (Roy et al., 2010). The culture temperature range for this species is 26–33°C (Wickins and Lee, 2008), and it can endure salinities of 0.5 to 45 ppt (Lester and Pante, 1992).

A significant percentage of all farmed penaeid shrimp are reared in low-salinity water (Flaherty et al., 2000). There is considerable interest in the culture of whiteleg shrimp far from coastal areas in inland ponds filled with low-salinity water (2–5 ppt). In southern USA, this tropical species is cultured in earthen ponds from early May through late October when the temperature is suitable (Green, 2008). Although ponds were constructed in soil of similar properties, filled with water from the same source, and stocked with postlarvae (PL) from the same sources, there were wide variation in shrimp performance among ponds. For example, at an inland, low-salinity shrimp farm in Alabama with 20 ponds, during 2008, survival in individual ponds ranged from 16 to 128%, production ranged from 928 to 5,950 kg/ha and feed conversion ratio (FCR) ranged from 1.18 to 2.89 (Prapaiwong and Boyd, 2012a, b).

Factors affecting fish or shrimp growth include water temperature, water quality, feeding rates, diet composition, fish or shrimp weight, stocking density, and other variables (Brett, 1979). In general, the rate of physiological processes increase as the temperature and dissolved oxygen concentration increase (Buentello et al., 2000). The main controlling factor for fish or shrimp feeding, metabolism, and growth is temperature. The growth rate is reduced if the energy demand of increased metabolic rate exceeds the gain from increased food consumption (Brett, 1979). When food supply is not limiting, the specific growth rate of most aquatic species increases with rising temperature (Talbot, 1993).

Temperature is a vital factor controlling crustacean growth rates. The growth of *L. vannamei* is highly sensitive to small changes in temperature between 23 and 27°C, because of the large temperature coefficient for growth. The optimum temperature is size-specific and decreases when shrimp size increases; it is more than 30°C for small shrimp while it is about 27°C for large shrimp (Wyban et al., 1995). Further increases in temperature will adversely affect growth (Brett, 1979). When temperature is below 23°C, all sizes of shrimp are negatively affected, and when temperature exceeds 30°C, feed consumption and growth of large shrimp decline (Wyban et al., 1995).

Adverse temperature, salinity, and dissolved oxygen concentration are environmental stressors known to suppress crustacean immune responses. The production potential will be impaired when the water temperature falls outside the optimum range for significant periods (Wickins and Lee, 2008). One night with a minimum air temperature ≤ 14ºC may cool water in ponds sufficiently to kill *L. vannamei* (Green, 2008). Increasing temperature also results in greater oxygen production by phytoplankton in pond water. Of course, increasing the temperature also increases oxygen consumption by all organisms in a pond. If the oxygen consumption rate exceeds the rate of oxygen production, a critical situation with low dissolved oxygen concentration occurs (Kepenyes and Váradi, 1984).

Annual variation in water temperature patterns affects shrimp and fish production in ponds (Boyd and Pine, 2010), but little attention has been given to daily, monthly, or seasonal variations in temperature among ponds. Consequently, the present study was designed to determine water temperature pattern in different ponds and different years on a shrimp farm and to evaluate the possible contribution of bottom water temperature to variation in survival, production, and FCR.

4.3. Methods and Materials

4.3.1. Farm and management

The study was conducted during four annual grow-out cycles – 2012 to 2015 – at Greene Prairie Aquafarm, an inland, low-salinity shrimp farm. Whiteleg shrimp are produced at high density in ponds using feed-based culture and mechanical aeration. This farm is located in the Blackland Prairie region of west-central Alabama, about 5 km north of Forkland, Alabama on the west side of US Highway 43 in the southeastern Greene County at GPS coordinates 32° 41' 40.8" N, 87° 54' 10.0" W. In 2012 and 2013, the farm consisted of 20 earthen-lined ponds, then two ponds were newly-built. Thus, in 2014 and 2015, the farm had 22 ponds (Figure 4.1), ranging from 0.49 ha to 2.02 ha in water surface area for a total of 28.9 ha (Table 4.1). Average depths varied from 1.16 m to 1.77 m (average = 1.41 m). The water source was two wells that draw from a saline aquifer (3.7 ppt salinity). Water exchange is not practiced on the farm, and water is added to the ponds at intervals to compensate seepage and evaporation losses. In each pond, the water level is maintained 10 –15 cm below the top of the overflow pipe to capture rainfall and runoff and avoid overflow.

Genetically-improved and specific-pathogen-free (SPF) postlarvae (PLs) were purchased by the middle of April from Shrimp Improvement Systems, LLC (SIS), Islamorada, Florida, USA and from Harlingen Shrimp Farms, Ltd, Los Fresnos, Texas, USA. During 2014 and 2015, SIS was the only source of PLs. In 2012, ponds were stocked at the density of 21.3 to 33 PL/m^2 (average = 27.8 PL/m^2) between 26 April and 22 May (Table 4.1). In 2013, ponds were stocked at densities of 21.5 to 30.4 PL/m^2 (average = 25 PL/m^2) between 9 May and 6 June (Table 4.1). In 2014, ponds were stocked at the density of 18.5 to 40.7 PL/m^2 (average = 29.5 PL/m^2) between 9 May and 31 May (Table 4.1). In 2015, ponds were stocked between 5 May and 3 June; the pond N-6 was stocked at the density of 75 PL/m^2 while no PLs were stocked in N-7. The other 20 ponds were stocked at the density of 26.3 to 45.1 PL/m^2 (average = 29.1 PL/m^2) (Table 4.1). A commercial, pelleted feed containing 35% crude protein was applied twice daily, and the amounts used in each pond were recorded. A 10-hp electric paddlewheel aerator was installed in each pond. Aerators were operated mostly at night.

4.3.2. Water and air temperatures

The water temperature in each pond and air temperature were monitored with Model 64K HOBO Pendant® Temperature/Alarm Data Loggers (UA-001-64, HOBOware®, Ben Meadows, Janesville, Wisconsin, USA). The manufacturer reported that these loggers have an accuracy of 0.47˚C at 25˚C and a resolution of 0.10˚C. The difference among these loggers at the same temperature was determined to be no more than 0.27˚C (Prapaiwong and Boyd, 2012a). The temperature loggers were programmed to monitor temperature at 1-h intervals. Water temperature loggers were attached to tops of concrete blocks (20 cm tall) and placed at 1.2 m depth in each pond – about 5 cm above the pond bottom. The data logger for monitoring air temperature was mounted at a height of 3 m under an open tractor shed — roof but no sides — located within 700 m of the most distant pond. For four growing seasons, water temperature in each pond and air temperature were recorded starting the day before stocking and continuing until harvest. At harvest, data loggers were removed from ponds and connected to the computer using HOBO Pendant Optic USB Base Station and Coupler (part # BASE-U-1). Software provided by the manufacturer (HOBOware Pro 3.7.1) was used to download data into a laptop computer.

The hourly water temperature data from each pond were used to calculate the average, range, maximum, minimum, and coefficient of variation (CV) of air and water temperature on each of a weekly, monthly, and culture period (estimated from stocking to harvest) basis. Also, the grand mean for all ponds was calculated on the basis of the average of hourly temperature data.

The hourly water temperature data were used to create four new variables. The new variables are representing the count of hours that fell into one of four temperature zones. The variable (best) is the count of the hours when water temperature was between 26 and 28°C, the variable (optimum range) is the count of the hours when water temperature was between 23 and 30°C, the variable (tolerated range) is the count of the hours when water temperature ranged from 15 to less than 23°C (low tolerated) or ranged from more than 30°C to less than 33°C (high tolerated). The variable (extreme) is the count of the hours when water temperature was less than 15°C or higher than 33°C (Figure 4.2). The percentage of the hourly water temperature values that fell in a certain temperature zone was calculated on weekly and culture period basis as follows:

$$(\%) = \frac{\text{Count of hours that fell in that temperature zone during (week or growing season)}}{\text{Total number of hours recorded during that (week or growing season)}} \text{X100}$$

The hourly water temperature data were also used to create another 36 variables representing the count of hours that fell into one of the 36 narrow temperature ranges. These ranges are of 0.5°C interval between 15°C to 33°C. For instance, the first temperature range was recording the count of hours when water temperature falls between 15 and 15.5°C. In addition, the percentage of hourly water temperature that fell in a certain temperature range was calculated in the same way as for the four temperature zones.

4.3.3. Shrimp performance

After the annual harvest, the farm manager provided the sampling data and the harvest data for each pond. During each growing season, the farm manager sampled shrimp growth every 7–10 days by the aid of cast net. There were 20 – 22 weekly samples for each growing season. The sampling data included the weekly estimated survival rate % (Sr_W), weekly average weight (g) of shrimp (W_w) in each pond and their corresponding date. In addition, the harvest performance data of each pond included the source of PLs, the initial number of stocked PLs, average initial weight (g) of the stocked PLs (W_i), stocking and harvesting dates, total shrimp production (kg), average final weight (g) of the harvested shrimp (W_f), the number of the harvested shrimp, and the amount of feed provided (kg).

The absolute weight gain (g/wk) of shrimp (WG) was calculated for each pond at the end of each growing season **(**WG_f) and at weekly basis **(**WG_w), as shown below:

WG_f (g/wk) of shrimp at harvesting = $\frac{W_f - W_i}{(D_{(h)} - D_{(s)})/7}$

where $D_{(h)}$ = harvesting date; $D_{(s)}$ = stocking date.

WG_w (g) of shrimp at the sample number (X+1) = $\frac{(W_{(x+1)} - W_{(x)})}{(D_{(x+1)} - D_{(x)})/7}$

where $W_{(x)}$ = mean weight (g) at the sample number (x); $W_{(x+1)}$ = mean weight (g) at the sample number (x+1); $D_{(x)}$ = date of the sample number (x); $D_{(x+1)}$ = date of the sample number (x+1).

The weekly relative growth rate (Gr_w) at any sample (%) was calculated and expressed as a percentage of the mean weight of its previous sample, as shown below:

Gr_w (%) of shrimp at the sample number (X+1) = $\frac{100\ (W_{(x+1)} - W_{(x)})}{W_{(x)}\ (\frac{D_{(x+1)} - D_{(x)}}{7})}$

The stocking density (PL/m^2) was calculated for each pond from the initial number of PLs and surface area of the pond. The crop duration (days) was calculated for each pond from the difference between harvesting and stocking dates. The shrimp production per unit area (kg/ha/crop) and production per unit area per day (kg/ha/d) were calculated for each pond from total shrimp production, the surface area of the pond, and the crop duration. The final survival rate % (Sr_f) was calculated for each pond from the difference between number of the stocked PLs and number of the harvested shrimp. Also, the FCR was calculated for each pond from the amount of feed provided and the weight gain of the shrimp.

4.3.4. Statistical analysis

Pearson's r correlation analyses were conducted on culture period performance data to find significant correlations between temperature variables, stocking density, pond surface area, pond depth, pond surface area:volume ratio (SA:V), and crop duration versus W_f, FCR, Sr_f, production (kg/ha) and production rate (kg/ha/d). All multiple testing *p*-values for correlation analyses have been adjusted to control the false discovery rate (FDR) using the Benjamini-Hochberg procedure (Benjamini and Hochberg, 1995). As Gr_w is affected by shrimp weight, it is obviously correlated with the sampling week, i.e. in first couple weeks the growth rate was a very high percentage then it decreased gradually during subsequent weeks. To avoid the effect of this correlation, the Gr_w was z-transformed for each sample independently using the Gr_w means and standard deviations. The Sr_w also decreased from week to week; therefore, the Sr_w was standardized in the same manner as was Gr_w. The resulting standardized variables approximated a Gaussian distribution and were used in subsequent analysis.

To investigate the role of water temperature in determining variations in shrimp performance variables among ponds, linear mixed effects models (LMMs) with a Gaussian error structure were used. Each shrimp performance variable was considered as a response variable in a separate LMM. These models account for within pond variability and yearly clustering. Ponds were considered as subjects and data were stratified by year. Therefore, ponds and years were considered as random effects. Fixed factors included in LMMs were the crop duration range of water temperature in each pond, the percentage of hours that fell into best temperature zone during each growing season, the percentage of hours that fell out of the best temperature zone during each growing season, and the percentage of hours that fell into the following temperature ranges (26.5 – 27°C; 27 – 27.5°C; and 27.5 – 28°C). All LMMs were modeled with no intercept. Log transformations were applied to some variables in order to meet assumptions of normality and homogeneity. The variance explained was evaluated using $R^2_{LMM\ (m)}$, the marginal R^2 which is concerned with the variance explained by the fixed factors, and $R^2_{LMM(c)}$, the conditional R^2 which describes the proportion of variance explained by both the fixed and random factors (Nakagawa and Schielzeth, 2013). The $R^2_{LMM(c)}$ value was taken as the estimate of goodness-of-fit. Intraclass correlation coefficient was calculated to estimate the proportion of the variance of the random effects explained by each random effect (Bartko, 1976).

Data were also analyzed using means, standard deviations (*SD*), and simple linear regression. The Shapiro–Wilk test was utilized for normality analysis of the variables. Analysis of variance (ANOVA) was used for data with a normal distribution, and if there were significant differences, the Tukey's Studentized Range (HSD) test was used for post hoc analysis. Otherwise, the non-parametric Kruskal–Wallis test was used for data which were not normally distributed, and Wilcoxon Signed Ranks test was used to calculate the difference between samples in cases showing differences with the Kruskal–Wallis test. Statistical significance was set at $P < 0.05$, and all data were presented as the mean ± standard error of the mean (*SE*). The *F* and *P* values were calculated using Satterthwaite (1946) approximations. Analyses were performed with SAS® version 9.4 (SAS, 2013).

4.3.5. Mapping

An ESRI World Imagery basemap layer was obtained through ESRI online data service to provide cartographic context. This basemap is not regularly updated; it contained only 20 ponds at the farm—the case two years ago. Thus, a recent imagery base of the study farm was obtained using Google Earth. Georeferencing and rectification were performed to assign spatial coordinates to the recent two ponds obtained from Google Earth. Shapefiles (polygons) were created for each pond and for the shed. All polygons' contours were digitized on the map. Attribute data entry was performed for water temperature and shrimp production data. Layer properties were set. ArcGIS 10.3 (ESRI, 2015) was used for all geoprocessing and cartographic operations. ArcGIS is a geographic information system (GIS) program that allows datasets to be combined in digital “layers” based on shared geography.

4.4. Results and Discussion

4.4.1. Temperature

During the four-year study, air temperature data were successfully retrieved from data loggers for all years. Temperature data loggers were set up in each pond every year; however, usable data were not obtained from all of them. This happened when the data logger was not on the mooring at the end of the season, a technical error occurred that deleted the data or stopped logging process at a certain point, or the data logger was found floating on the pond surface – as in all ponds during 2014 growing season. All in all, water temperature data were successfully retrieved from 17 ponds during 2012, 15 ponds during 2013, and 15 ponds during 2015. The temperature data were obtained from all ponds at least on one year except for pond (N-13).

The grand mean (all ponds and years) of hourly water temperature was 29.10 ± 0.01°C (n = 151319). The annual averages (all ponds by year) of hourly water temperature were 29.03 ± 0.01°C during 2012 (n = 59174), 29.21 ± 0.01°C during 2013 (n = 49440), and 29.16 ± 0.01°C during 2015 (n = 42705). During the entire crop, the averages of hourly air temperatures were 25.01 ± 0.08°C during 2012 (n = 4190), 25.37 ± 0.07°C during 2013 (n = 3984), 25.35 ± 0.08°C during 2014 (n = 3984), and 25.89 ± 0.08°C during 2015 (n = 3865).

Across the entire culture period, the average water temperatures in individual ponds ranged from 28.52 to 29.88°C– a difference of 1.36°C during 2012 (Table 4.2; Figure 4.3). The ranges were from 28.59 to 30.02°C– a difference of 1.42°C during 2013, and from 28.29

to 30.40°C– a difference of 2.11°C during 2015. The monthly farm ranges of hourly water temperature (maximum − minimum) were 12.54°C in May, 10.1°C in June, 9.43°C in July, 8.67°C in August, 19.13°C in September, and 17.5°C in October during 2012; 12.8°C in May, 11.28°C in June, 7.67°C in July, 8.55°C in August, 17.9°C in September, and 13.67°C in October during 2013; and 19.39°C in May, 10°C in June, 9.51°C in July, 8.27°C in August, 19.46°C in September, and 11.33°C in October during 2015.

The weekly average water temperature in individual ponds ranged from 21.76°C to 32.86°C during 2012, 22.55 to 32.02°C during 2013, and 20.15 to 33.25°C during 2015. The weekly range (maximum − minimum) of hourly water temperature in individual ponds varied between 2.09 and 17.22°C during 2012, it varied between 1.28 and 14.20°C during 2013, and it varied between 1.75 and 19.46°C during 2015.

Both air temperature ($F = 25.78$; $p < 0.0001$) and water temperature ($F = 166.26$; $p < 0.0001$) were different among years. The hourly water temperatures were different among the ponds during 2012 ($F = 74.30$; $p < 0.0001$), 2013 ($F = 92.68$; $p < 0.0001$), and 2015 ($F = 116.48$; $p < 0.0001$). The hourly differences in water temperature among shrimp ponds (Figure 4.4) were as much as 11.99°C on 7 October 2012 (Ordinal date [OD] = 281), 10.64°C on 22 September 2013 (OD = 265), and 9.77°C on 24 September 2015 (OD = 267). The variation in temperature among ponds could have resulted from different aeration amounts (Abdelrahman and Boyd, submitted manuscript, 2015) or possibly because of different turbidity levels among ponds that can cause water temperatures to differ (Idso and Foster, 1974).

4.4.2. Shrimp performance

In 2015, ponds N-6 and N-7 were connected together as a trial of split-pond system, in which the PLs were stocked into one pond only while the other pond was a waste cell

(Tucker and Kingsbury, 2010). Therefore, the data from N-6 and N-7 during 2015 were excluded. Shrimp were harvested between 5 September and 18 October in 2012, between 10 September and 24 October in 2013, between 4 September and 21 October in 2014, and between 9 September and 22 October in 2015 (Table 4.3). In the study farm, shrimp performance varied greatly among ponds as follows: yield: 1,179 – 5,970 kg/ha/crop in 2012; 681 – 6,550 kg/ha/crop in 2013; 1,166 – 5,008 kg/ha/crop in 2014; and 717 – 5,772 kg/ha/crop in 2015 (Table 4.3; Figure 4.5); daily production rate: 9.7 – 41.4 kg/ha/day in 2012; 7.1 – 46.8 kg/ha/day in 2013; 8.5 – 37 kg/ha/day in 2014; and 5.7 – 37.7 kg/ha/day in 2015 (Table 4.3). The FCR also varied from 1.3 to 4.4 in 2012, from 1.2 to 2.9 in 2013, from 1.0 to 6.1 in 2014, and from 1.0 to 2.8 in 2015 and W_f, 20.3 – 38.5 g in 2012, 22.9 – 36 g in 2013, 22 – 38.8 g in 2014, and 20.2 – 41.3 g in 2015 (Table **4.4**).

The WG_f ranges were 0.89 – 2.53 g/week in 2012, 0.98 – 2.63 g/week in 2013, 1.01 – 2.54 g/week in 2014, and 1.05 – 2.31 g/week in 2015 (Table 4.3), and Sr_f, 14 – 89% in 2012, 8.5 –104% in 2013, 13.3 – 65.4% in 2014, and 23.4 – 77.8% in 2015 (Table **4.4**). It was common to have shrimp survival rates over 100% because of errors incurred in counting tiny PLs (Prapaiwong and Boyd, 2012b). Shrimp yield (kg/ha/crop) was different among years ($F = 4.49$; $p = 0.0058$) and Sr_f was significantly different among years ($F = 8.28$; $p < 0.0001$). Regardless of the year, shrimp yield was not different among ponds ($F = 1.39$; $p = 0.1613$), and Sr_f was not different among ponds ($F = 0.97$; $p = 0.5099$). Therefore, in each growing season, the variations in shrimp yield and Sr_f among ponds were not because of the ponds themselves. The performance of shrimp in a pond was good in one year and bad in another year (Figure 4.5).

There were variations in all shrimp performance variables that were determined on a weekly basis. The differences in the weekly shrimp weight among individual ponds ranged from 0.64 g to 18.3 g (average = 8.27 g) during 2012, from 0.5 g to 18.1 g (average = 8.39 g) during 2013, and from 0.31 g to 16.03 g (average = 11.21 g) during 2015. The weekly differences in the estimated shrimp survival rate among individual ponds varied from 5% to 70% (average = 33%) during 2012, from 4 to 75% (average = 41%) during 2013, and from 9 to 50% (average = 34%) during 2015. The weekly shrimp performance data for 2014 were not available.

4.4.3. Correlations between shrimp performance and temperature

4.4.3.1. Culture period correlations

During the four growing seasons, Sr_f was correlated with crop duration ($r = 0.47$, $p < 0.0001$, n = 82); shrimp yield was correlated with the crop duration ($r = 0.55$, $p < 0.0001$, n = 82). The crop duration was negatively correlated with average culture period water temperature while it was positively correlated with CV of hourly water temperature, and with the count of hours that fell into the following temperature zones: out of best, out of optimum, and tolerated temperature (Table 4.5). Of course, when the crop duration was longer, either early stocking or late harvesting, it extended the number of cooler days, which lowered the average water temperature, increased the temperature variation, and the count of undesirable temperature hours.

Pond depth was not correlated with any of the shrimp performance variables and water temperature variables (Table 4.6). The correlations of all shrimp performance and water temperature variables with surface area: volume ratio (SA:V) were not significant (Table 4.6) which agreed with observations by Prapaiwong and Boyd (2012a) during the 2010 growing season at Greene Prairie Aquafarm.

The WG_f was correlated (Table 4.5) with average culture period water temperature in each pond. Shrimp W_f and WG_f were negatively correlated with CV of hourly water temperature and the count of hours that fell into the following temperature zones: out of best, out of optimum, and tolerated temperature (Table 4.5).

There was a correlation between FCR and average culture period water temperature (*r* = 0.56, *p* = 0.0457) during 2012, while these variables were not correlated during 2013 (*r* = -0.35, *p* = 0.2171) or during 2015 (*r* = 0.59, *p* = 0.2171). During harvesting, the farm manager found dead shrimp exhibiting red coloration in ponds N-10, N-11, N-12, and S-1 in 2012; and N-12 in 2013. The farm manager overestimated the survival rate in these ponds during weekly sampling and applied excessive feed resulting in a high FCR. When the FCR of these ponds were omitted, no correlations between FCR and average culture period water temperature were found even in 2012. During the study, FCR was negatively correlated with the count of hours that fell into the tolerated temperature zone (*r* = -0.48, *p* = 0.0205, n = 45).

Shrimp yield was correlated with CV of hourly water temperature during 2015 (*r* = 0.95, *p* = 0.0132), while it was not correlated during 2012 (*r* = 0.49, *p* = 0.0516) and 2013 (*r* = 0.35, *p* = 0.2076). During the study, the *L. vannamei* yield was inversely correlated with the count of hours when water temperature was above 33°C (*r* = -0.43, *p* = 0.0240, n = 45), while it was positively correlated with the count of hours that fell into the optimum temperature zone (*r* = 0.36, *p* = 0.0240, n = 45), especially with the count of hours that fell into temperature ranges between 23.5 – 24°C (*r* = 0.48, *p* = 0.0132, n = 45), 24 – 24.5°C (*r* = 0.37, *p* = 0.0343, n = 45), 24.5 – 25°C (*r* = 0.41, *p* = 0.0240, n = 45), and 25 – 25.5°C (*r* = 0.40, *p* = 0.0240, n = 45). Shrimp yield was also correlated with the count of hours that fell into tolerated temperature zone (*r* = 0.49, *p* = 0.0039, n = 45), especially with the count of hours that fell into temperature ranges between 30 – 30.5°C (*r* = 0.56, *p* = 0.0039, n = 45), 30.5 – 31°C (*r* = 0.47, *p* = 0.0132, n = 45), and 31 – 31.5°C (*r* = 0.41, *p* = 0.0240, n = 45). When shrimp in a pond were exposed to temperature above 33°C for more hours, the production potential of this pond was impaired. In contrast, when shrimp in a pond were exposed to temperature between 23.5 – 25.5°C or between 30 – 31.5°C for more hours, the shrimp yield of this pond tended to increase.

The production, of course, is the result of survival and growth; the Sr_f was inversely correlated with average culture period water temperature (r = -0.55, p = 0.0349) during 2012 (Table 4.5), but not correlated during 2013 (r = -0.12, p = 0.6764), or during 2015 (r = -0.29, p = 0.1136). Over the three years, Sr_f was correlated with the CV of hourly water temperature (r = 0.50, p = 0.0058, n = 45) (Table 4.5), the count of hours that fell out of best zone (r = 0.62, p = 0.0003, n = 45), the count of hours that fell out of optimum zone (r = 0.73, p = 0.0003, n = 45), and the count of hours that fell into extreme zone (r = 0.77, p = 0.0003, n = 45).

Ponds with poor survival were harvested earlier either intentionally or by chance. Therefore, the crop duration of these ponds did not extend to cooler fall days; such ponds had higher average and less variation in temperature, and less count of hours that fell into undesirable temperature ranges. Nevertheless, correlations between weekly shrimp performance and water temperature variables would be needed to verify the influence of variations in water temperature on shrimp growth, survival, and growth.

4.4.3.2. Weekly correlations

During the study, Sr_w was positively correlated with weekly range of water temperature in individual ponds, weekly maximum water temperature in an individual pond, the count of hours that fell into optimum temperature zone, and the count of hours that fell into the best temperature zone, especially with the count of hours that fell into temperature ranges of 27 – 27.5°C and 27.5 – 28°C (Table 4.7). While the Sr_w was negatively correlated with the count of hours that fell into temperature ranges of 17.5 – 18°C, 18 – 18.5°C, 18.5 – 19°C, 19 – 19.5°C, 19.5 – 20°C, and 20 – 20.5°C (Table 4.7).

The W_w was negatively correlated with the count of hours that fell into optimum temperature zone, that fell into best temperature zone, especially with the count of hours that fell into temperature ranges of 27 – 27.5°C, 27.5 – 28°C, and 28 – 28.5°C (Table 4.7). The W_w was also negatively correlated with the weekly maximum water temperature in an individual pond, weekly average of hourly water temperature in an individual pond, and weekly range of water temperature in an individual pond (Table 4.7). While the W_w was positively correlated with the count of hours that fell into temperature ranges of 17.5 – 18°C, 18 – 18.5°C, 18.5 – 19°C, 19 – 19.5°C, 19.5 – 20°C, and 20 – 20.5°C (Table 4.7).

The Gr_w was positively correlated with weekly range of water temperature in individual ponds, the weekly *SD* of hourly water temperature in individual ponds, the weekly CV of hourly water temperature in individual ponds, count of hours that fell into best temperature zone, and count of hours that fell into optimum temperature zone, especially with the count of hours that fell into temperature ranges of 26 – 26.5°C, 26.5 – 27°C, 27 – 27.5°C, 27.5 – 28°C, and 28 – 28.5°C (Table 4.8). While the Gr_w was negatively correlated with weekly average of hourly water temperature in individual ponds, count of hours that fell out of the best temperature zone, the count of hours that fell out of the optimum temperature zone, and the count of hours that fell into tolerated temperature zone (Table 4.8). The Gr_w was negatively correlated especially with the count of hours that fell into temperature ranges of 30 – 30.5°C, 30.5 – 31°C, 31 – 31.5°C, 31.5 – 32°C, 32 – 32.5°C, and 32.5 – 33°C (Table 4.8).

The WG_w was negatively correlated with weekly range of water temperature in individual ponds, the weekly CV of hourly water temperature in individual ponds, the count of hours that fell into the best temperature zone, and the count of hours that fell into optimum temperature zone (Table 4.8). The WG_w was negatively correlated especially with the count of hours that fell into temperature ranges of 24 – 24.5°C, 24.5 – 25°C, 25 –

25.5°C, 25.5 – 26°C, 26 – 26.5°C, 26.5 – 27°C, 27 – 27.5°C, and 27.5 – 28°C (Table 4.8). While the WG_w was positively correlated with the weekly average of hourly water temperature in an individual pond, the weekly maximum water temperature in an individual pond, the count of hours that fell out of the best temperature zone, that fell out of the optimum temperature zone, that fell into tolerated temperature zone (Table 4.8). The WG_w was positively correlated especially the count of hours that fell into temperature ranges of 30 – 30.5°C, 30.5 – 31°C, 31 – 31.5°C, 31.5 – 32°C, 32 – 32.5°C, and 32.5 – 33°C, and the count of hours with water temperature above 33°C (Table 4.8).

The weekly sum of hourly water temperature in an individual pond was positively correlated with Sr_w (Table 4.7), Gr_w (Table 4.8), and negatively correlated with W_w (Table 4.7). When an individual pond was exposed to more temperature degrees in a certain week, the higher the survival rate and growth rate and the smaller the shrimp size in this pond in this week.

The hourly average of water temperature in all ponds (hourly farm mean) was positively correlated with weekly average of WG_w in all ponds ($r = 0.69$, $p < 0.0001$, n = 10,883), weekly range of W_w among ponds (weekly farm range) ($r = 0.40$, $p < 0.0001$, n = 11,411), and weekly range of Sr_w among ponds ($r = 0.26$, $p < 0.0001$, n = 11,411), while it was negatively correlated with weekly range of WG_w among ponds ($r = -0.22$, $p < 0.0001$, n = 10,883). The higher the water temperature at the farm, the greater the weekly weight gain, with more variation in weekly shrimp size and weekly survival rate among ponds, and less variation in weekly weight gain among ponds.

Nevertheless, the hourly range (maximum − minimum) of water temperature among ponds (hourly farm range) was negatively correlated with weekly range of W_w among ponds ($r = -0.30$, $p < 0.0001$, n = 11,411) and weekly range of Sr_w among ponds ($r = -0.29$, $p <$ 0.0001, n = 11,411). The hourly CV of water temperature among ponds was negatively correlated with weekly range of W_w among ponds (*r* = -0.37, *p* < 0.0001, n = 11,411) and weekly range of Sr_w among ponds (*r* = -0.33, *p* < 0.0001, n = 11,411). The findings suggest that the increase in temperature variability among ponds agreed well with the diminishing variation in survival and weight of shrimp observed among ponds.

4.4.4. Linear Mixed Models

LMMs were conducted using each harvest shrimp performance variable as a response variable in a separate model. The variance in FCR among ponds explained ($R^2_{LMM\ (m)}$) by the percentage of hours for each pond that fell into the temperature ranges as follows: 26.5 – 27°C was 27%; 27 – 27.5°C was 32.7%; 27.5 – 28°C was 18.7%. The crop duration range of water temperature in each pond explained 4.2% of the variance in FCR. The variance in W_f among ponds explained by the crop duration range of water temperature in each pond was 41%; in this LMM, the ponds were significant as a random effect (*Z* = 1.78, *p* = 0.0378). The intra-pond correlation coefficient was 0.40; which means that independently of water temperature, the pond itself explained 40% of the variance of the random effects in this model.

Moreover, the percentage of hours that fell out of the best temperature zone explained 4.3% of the variance in W_f. The variance in shrimp production per unit area explained by the percentage of hours that fell into the best temperature zone for each pond was 5.9%. The variance in shrimp production per unit area per day explained by the crop duration range of water temperature in each pond was 5.2%. The variance in WG_f explained by percentage of hours for each pond that fell into the following temperature ranges: 26.5 – 27°C was 7.7%; 27 – 27.5°C was 11.8%; 27.5 – 28°C was 7%.

4.5. Conclusions

Although ponds were constructed in a soil of similar properties, filled with water from the same source, stocked with PLs from same sources, and receive the same management practices, there were daily, monthly, and seasonal variations in water temperature patterns among these shrimp ponds. The greatest monthly variations in water temperature were during May, September, and October. These variations affected shrimp growth, survival, and production, and there were wide variations in shrimp performance – both weekly and at the end of each growing season – among these ponds. Pond depth and SA:V ratio were not correlated with any of the water temperature or shrimp performance variables. Features of the ponds themselves were not the reason behind the variation in shrimp yield and survival among ponds.

In individual ponds, the shrimp weight gain increased with higher average water temperature during the growing season, while shrimp weight and weight gain decreased with increasing variation in water temperature in individual ponds. Considering shrimp performance in all ponds, the higher the water temperature, the greater the weekly weight gain, with more variation in weekly shrimp size and weekly survival rate among ponds, and less variation in weekly weight gain among ponds. The increase in temperature variability among ponds agreed well with the diminishing variation in survival and weight of shrimp observed among ponds.

Shrimp yield was better when water temperature was between 23.5 – 25.5°C and 30 – 31.5°C for more hours, while shrimp yield and FCR tended to be worse when water temperature was above than 33°C for more hours. The weekly growth rate was better when water temperature was between 26 – 27.5°C for more hours. The variance in shrimp production was best explained by temperature between 26–28°C; variance in FCR and in weight gain was best explained by temperature between 27–27.5°C; variance in average final weight of the harvested shrimp was best explained by the crop duration range of water temperature in individual ponds. In conclusion, bottom water temperature has a major influence on the variations in shrimp performance among ponds.

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Table 4.1 Means, standard deviations (*SD*) for pond areas and depths, stocking density, stocking dates and amounts of feed applied to 22 study ponds at an inland, low-salinity farm in Alabama during the 2012, 2013, 2014 and 2015 growing seasons.

Pond	Depth (m)	Area (ha)	Stocking data								Feed applied (Kg/ha)			
			PLs/m^2				Date							
			2012	2013	2014	2015	2012	2013	2014	2015	2012	2013	2014	2015
N-1	1.41	0.49	31	26	31	27	22-May	14-May	22-May	5-May	7,577	6,325	8,079	6,693
N-2	1.32	0.57	33	25	31	27	22-May	14-May	22-May	7-May	4,410	5,867	5,775	6,885
N-3	1.44	1.09	29	25	34	27	27-Apr	14-May	21-May	7-May	7,325	7,267	8,634	6,077
N-4	1.43	1.21	25	25	32	45	30-Apr	13-May	21-May	2-Jun	7,804	8,949	6,785	7,649
N-5	1.22	1.34	26	25	28	28	28-Apr	13-May	22-May	7-May	8,898	8,353	8,214	6,989
N-6	1.34	1.5	26	25	30	75*	28-Apr	13-May	9-May	2-Jun	8,949	8,744	6,479	14,213*
N-7	1.77	2.02	26	23	30	0*	28-Apr	6-Jun	21-May	2-Jun	8,757	5,446	9,461	0*
N-8	1.43	1.54	26	24	32	27	30-Apr	13-May	21-May	5-May	6,786	8,220	7,931	7,773
N-9	1.44	1.62	21	23	29	26	30-Apr	14-May	22-May	7-May	5,717	5,850	8,067	5,283
N-10	1.41	1.62	26	22	26	27	27-Apr	27-May	22-May	5-May	5,775	6,121	3,473	6,297
N-11	1.41	1.54	26	22	31	28	22-May	13-May	9-May	5-May	5,166	7,843	8,364	7,521
N-12	1.41	1.9	28	22	18	30	22-May	6-Jun	22-May	5-May	5,311	1,687	2,751	5,543
N-13	-	1.21	-	-	41	28	-	-	21-May	5-May	-	-	6,367	8,164
N-14	-	0.81	-	-	31	28	-	-	21-May	5-May	-	-	6,368	7,670
S-1	1.16	1.17	29	25	26	27	26-Apr	27-May	9-May	5-May	6,622	6,110	5,299	6,840
S-2	1.4	0.89	29	25	25	31	26-Apr	14-May	31-May	2-Jun	9,061	5,794	2,669	7,591
S-3	1.19	1.01	32	30	20	29	22-May	27-May	31-May	7-May	6,305	10,337	5,593	4,533
S-4	1.67	1.09	26	26	30	29	22-May	27-May	9-May	3-Jun	5,434	8,908	7,683	3,862
S-5	1.47	0.97	30	25	31	29	11-May	27-May	22-May	5-May	7,992	9,817	10,302	8,785
S-6	1.51	1.42	29	26	30	27	26-Apr	9-May	9-May	7-May	6,827	9,778	6,714	5,445
S-7	1.29	1.9	28	29	29	32	26-Apr	9-May	9-May	2-Jun	6,585	8,522	6,967	5,561
S-8	1.49	1.94	28	25	33	28	26-Apr	14-May	9-May	3-Jun	8,116	7,151	9,841	4,451
Mean	1.41	1.34	27.77	25.00	29.49	29.83	-	-	-	-	6971	7355	6901	6537
SD	0.14	0.43	2.63	2.07	4.48	12.15	-	-	-	-	1368	1974	2037	2490

* In 2015, N-6 and N-7 were connected together to form split-pond system. N-7 had neither PLs nor feed.
Ponds N-13 and N-14 were newly constructed in 2014. Their depths were not measured.

Table 4.2 Monthly averages, standard deviations (*SD*), and coefficient of variation (CV) for water temperature during the 2012, 2013 and 2015 growing seasons in 21 ponds at an inland, low-salinity shrimp farm in Alabama. The letter S designated that ponds were stocked in May and could not be used in average. The letter H designated that ponds were harvested in September.

Pond	**May**			**June**			**July**			**August**			**September**			**October**			**Mean**[b]		
	2012	**2013**	**2015**	**2012**	**2013**	**2015**	**2012**	**2013**	**2015**	**2012**	**2013**	**2015**	**2012**	**2013**	**2015**	**2012**	**2013**	**2015**	**2012**	**2013**	**2015**
N-1	29.95	26.77	25.17	29.94	30.57	30.01	31.38	30.58	31.51	29.82	30.65	30.46	27.58	29.51	27.65	H	H	H	29.71	29.89	29.32
N-2	-	25.66	25.20	-	28.95	29.37	-	29.58	30.65	-	30.24	29.98	-	29.94	27.60	-	H	23.34	-	29.08	28.64
N-3	27.91	26.31	26.03	29.98	30.28	30.47	31.37	30.25	31.49	29.92	30.64	30.43	28.25	29.51	29.64	H	H	H	29.60	29.69	29.97
N-4	27.52	26.91	S	29.86	30.24	29.39	31.12	29.83	31.25	29.60	30.27	30.32	27.17	28.54	27.89	23.92	25.28	21.78	29.03	29.13	28.60
N-5	-	27.05	-	-	30.12	-	-	29.91	-	-	30.55	-	-	28.87	-	-	H	-	-	29.49	-
N-6	26.83	25.94	S	29.62	30.04	29.73	31.24	29.99	31.68	29.77	30.40	30.50	27.11	28.52	27.97	22.34	24.37	26.32	28.52	28.85	29.99
N-7	28.06	-	S	29.73	-	28.61	31.18	-	31.63	29.88	-	30.37	27.39	-	27.74	22.88	-	20.86	28.69	-	29.26
N-8	27.11	25.58	25.93	29.70	29.80	30.19	31.29	30.13	31.58	30.03	30.71	30.52	28.79	28.95	28.09	H	25.35	22.20	29.45	28.97	29.36
N-9	26.93	-	-	29.39	-	-	31.06	-	-	29.81	-	-	27.57	-	-	H	-	-	29.00	-	-
N-10	26.87	25.22	24.98	29.37	29.07	29.07	30.86	29.79	31.10	29.48	30.37	29.89	28.46	28.73	28.27	H	25.33	H	29.13	29.27	29.04
N-11	28.40	22.85	24.70	30.12	29.80	28.89	31.30	30.15	31.07	29.71	30.52	30.06	28.23	28.77	27.91	H	25.97	H	29.88	28.76	28.89
N-12	28.08	S	23.44	29.52	27.98	29.68	31.15	29.31	31.06	29.65	29.87	30.23	27.10	30.35	29.63	H	H	H	29.53	29.24	29.25
N-14	-	-	26.49	-	-	30.15	-	-	31.39	-	-	30.43	-	-	27.95	-	-	22.55	-	-	28.98
S-1	27.68	27.69	26.37	29.36	30.04	29.85	31.03	29.96	31.44	29.57	30.42	30.16	27.38	30.02	27.65	H	H	20.80	29.07	30.02	28.93
S-2	27.30	-	S	29.72	-	29.99	31.26	-	31.73	29.73	-	30.45	27.23	-	27.94	22.75	-	21.53	28.71	-	28.77
S-3	29.16	27.85	-	29.97	28.89	-	31.18	29.75	-	29.72	30.35	-	27.26	28.47	-	22.56	24.23	-	28.85	28.59	-
S-4	29.76	-	S	29.82	-	28.05	30.45	-	30.84	29.22	-	29.74	27.17	-	27.61	22.77	-	22.31	28.52	-	28.29
S-5	27.56	27.50	-	29.56	29.55	-	31.20	29.73	-	29.96	30.12	-	27.49	28.73	-	22.94	25.15	-	28.60	29.00	-
S-6	26.54	-	-	29.23	-	-	30.84	-	-	29.58	-	-	28.69	-	-	H	-	-	29.03	-	-
S-7	-	24.68	-	-	30.00	-	-	30.05	-	-	30.64	-	-	28.86	-	-	25.16	-	-	28.75	-
S-8	26.97	26.92	S	29.53	29.87	30.36	31.24	30.24	31.90	29.97	30.83	30.66	27.48	30.12	28.18	23.19	H	H	28.80	29.82	30.40
Mean[a]	27.49	25.95	25.37	29.67	29.70	29.59	31.13	29.95	31.35	29.73	30.44	30.28	27.53	29.05	28.03	22.78	24.93	21.92	29.03	29.21	29.16
SD	2.00	2.35	1.88	1.80	1.61	1.82	1.78	1.36	1.85	1.33	1.72	1.39	1.87	2.23	2.08	1.78	1.81	2.34	2.53	2.38	2.93
Range[c]	3.40	5.00	3.05	0.89	2.59	2.42	0.94	1.27	1.25	0.81	0.96	0.92	1.68	1.88	2.04	1.58	1.74	5.51	1.36	1.42	2.11
CV (%)	7.28	9.06	7.39	6.07	5.41	6.14	5.72	4.53	5.91	4.47	5.65	4.59	6.80	7.68	7.42	7.79	7.24	10.70	8.71	8.16	10.05

[a] Monthly average of hourly water temperature in all ponds.

[b] Average of hourly water temperature in individual ponds in all months.

[c] Range is the difference between maximum and minimum pond averages of hourly water temperature.

Table 4.3 Harvest dates; means, standard deviations (*SD*) for crop duration, shrimp production (kg/ha/day), and weight gain (g/week) of the shrimp produced from 22 study ponds at an inland, low-salinity farm in Alabama during the 2012, 2013, 2014 and 2015 growing seasons.

Pond	**Harvest date**				**Crop duration (days)**				**Shrimp Production (Kg/ha/day)**				**Weight gain (g/week)**			
	2012	**2013**	**2014**	**2015**	**2012**	**2013**	**2014**	**2015**	**2012**	**2013**	**2014**	**2015**	**2012**	**2013**	**2014**	**2015**
N-1	1-Oct	25-Sep	20-Oct	30-Sep	132	134	118	148	41	29	11	20	1.39	1.54	1.90	1.70
N-2	5-Sep	18-Sep	30-Sep	7-Oct	106	127	107	153	25	31	27	29	2.53	1.90	2.05	1.41
N-3	19-Sep	26-Sep	14-Oct	15-Sep	145	135	131	131	35	45	35	23	1.44	1.39	1.50	1.99
N-4	2-Oct	9-Oct	25-Sep	21-Oct	155	149	158	141	37	41	22	28	1.33	1.39	1.18	1.51
N-5	4-Oct	30-Sep	2-Oct	21-Sep	159	140	148	137	34	47	26	25	1.22	1.28	1.17	1.67
N-6	11-Oct	13-Oct	9-Sep	1-Oct	166	153	132	121	33	30	22	38	1.05	1.11	1.37	1.50
N-7	16-Oct	2-Oct	21-Oct	-	171	118	137	-	30	30	25	-	0.95	1.84	1.12	-
N-8	18-Sep	15-Oct	7-Oct	5-Oct	141	155	157	153	15	31	29	23	1.52	1.15	1.00	1.16
N-9	27-Sep	16-Sep	15-Oct	9-Sep	150	125	151	125	20	26	25	15	1.25	1.54	1.32	1.59
N-10	6-Sep	3-Oct	16-Sep	24-Sep	132	129	131	142	18	32	21	20	1.52	1.28	1.75	1.60
N-11	20-Sep	7-Oct	30-Sep	29-Sep	121	147	146	147	10	32	32	18	1.85	1.22	1.23	1.45
N-12	17-Sep	10-Sep	11-Sep	14-Sep	112	96	127	132	14	7	21	19	1.49	2.63	1.35	1.73
N-13	-	-	1-Oct	19-Oct	-	-	133	167	-	-	28	19	-	-	1.51	1.30
N-14	-	-	24-Sep	13-Oct	-	-	123	161	-	-	21	23	-	-	2.10	1.30
S-1	26-Sep	19-Sep	4-Sep	8-Oct	153	115	153	156	13	35	25	24	1.76	1.42	1.07	1.50
S-2	10-Oct	12-Sep	15-Sep	22-Oct	167	121	139	142	29	16	9	35	1.07	1.72	1.95	1.26
S-3	15-Oct	22-Oct	9-Oct	9-Sep	146	148	146	125	30	40	29	27	1.17	1.12	1.66	2.31
S-4	17-Oct	21-Oct	14-Oct	17-Oct	148	147	117	136	21	44	31	27	1.45	1.15	2.07	1.70
S-5	18-Oct	16-Oct	17-Oct	14-Oct	160	142	144	162	33	41	32	36	0.89	1.16	1.29	1.12
S-6	12-Sep	24-Oct	18-Sep	17-Sep	139	168	112	133	31	37	44	15	1.46	0.98	1.70	1.26
S-7	24-Sep	14-Oct	23-Sep	15-Oct	151	158	133	135	34	39	9	36	1.22	1.01	1.37	1.05
S-8	8-Oct	23-Sep	13-Oct	25-Sep	165	132	126	114	36	45	40	18	1.02	1.35	1.31	1.27
Mean	-	-	-	-	145.95	136.95	134.95	140.32	26.9	34.0	25.6	24.6	1.38	1.41	1.50	1.53
SD	-	-	-	-	17.63	16.75	14.09	13.97	9.1	9.7	8.5	6.8	0.36	0.38	0.34	0.32

In 2015, N-6 and N-7 were connected together to form split-pond system. N-7 had neither PLs nor feed.
Ponds N-13 and N-14 were newly constructed in 2014.

Table 4.4 Means, standard deviations (*SD*) for shrimp yield (kg/ha/crop), final shrimp weight, survival rate (%), and feed conversion ratio (FCR) of the shrimp produced from 22 study ponds at an inland, low-salinity farm in Alabama during the 2012, 2013, 2014 and 2015 growing seasons.

Pond	**Shrimp Yield (Kg/ha/crop)**				**Final weight (g)**				**Survival (%)**				**FCR**			
	2012	**2013**	**2014**	**2015**	**2012**	**2013**	**2014**	**2015**	**2012**	**2013**	**2014**	**2015**	**2012**	**2013**	**2014**	**2015**
N-1	5,467	3,852	1,316	3,001	26.2	29.4	32	36	67.1	50.4	13.3	30.5	1.4	1.6	6.1	2.2
N-2	2,615	3,961	2,934	4,386	38.3	34.4	31.3	30.9	20.7	45.5	30.2	52.4	1.7	1.5	2.0	1.6
N-3	5,017	6,103	4,587	3,041	29.8	26.9	28	37.2	58.7	90.7	47.9	29.8	1.5	1.2	1.9	2.0
N-4	5,696	6,085	3,494	3,894	29.5	29.5	26.7	30.4	76.1	82.4	41.5	28.4	1.4	1.5	1.9	2.0
N-5	5,345	6,549	3,833	3,386	27.7	25.5	24.7	32.7	74.5	103.6	55.0	36.8	1.7	1.3	2.1	2.1
N-6	5,430	4,522	2,941	4,563	25	24.3	25.9	26	83.9	74.7	37.3	23.4	1.6	1.9	2.2	2.6
N-7	5,118	3,541	3,372	-	23.3	31	22	-	84.5	48.7	51.0	-	1.7	1.5	2.8	-
N-8	2,093	4,813	4,594	3,443	30.6	25.4	22.4	25.4	26.0	79.9	63.4	49.8	3.2	1.7	1.7	2.3
N-9	2,932	3,265	3,775	1,854	26.8	27.5	28.5	28.4	51.3	51.4	45.2	24.8	1.9	1.8	2.1	2.8
N-10	2,360	4,171	2,775	2,890	28.6	23.5	32.7	32.4	31.4	81.0	32.6	32.6	2.4	1.5	1.3	2.2
N-11	1,179	4,760	4,702	2,640	32	25.7	25.7	30.5	14.0	86.1	58.3	31.4	4.4	1.6	1.8	2.8
N-12	1,516	681	2,707	2,525	23.8	36	24.5	32.7	23.1	8.5	59.8	26.2	3.5	2.5	1.0	2.2
N-13	-	-	3,703	3,200	-	-	28.7	31.1	-	-	31.7	36.7	-	-	1.7	2.6
N-14	-	-	2,617	3,761	-	-	36.9	29.9	-	-	22.8	45.2	-	-	2.4	2.0
S-1	2,035	4,037	3,773	3,672	38.5	23.4	23.3	33.4	18.4	67.9	61.5	40.5	3.3	1.5	1.4	1.9
S-2	4,895	1,978	1,306	5,001	25.5	29.7	38.8	25.6	66.1	26.6	13.3	64.0	1.9	2.9	2.0	1.5
S-3	4,335	5,886	4,166	3,413	24.4	23.7	34.6	41.3	54.9	81.8	61.0	28.3	1.5	1.8	1.3	1.3
S-4	3,175	6,518	3,592	3,708	30.6	24.2	34.6	33.1	40.1	104.0	35.2	39.0	1.7	1.4	2.1	1.0
S-5	5,334	5,847	4,550	5,772	20.3	23.5	26.5	25.9	87.6	98.6	55.7	77.8	1.5	1.7	2.3	1.5
S-6	4,283	6,267	4,887	1,951	28.9	23.5	27.2	23.9	50.5	101.0	60.8	30.0	1.6	1.6	1.4	2.8
S-7	5,169	6,170	1,166	4,886	26.3	22.9	26.1	20.2	69.7	93.0	15.5	74.9	1.3	1.4	6.0	1.1
S-8	5,970	5,936	5,008	2,057	24.1	25.4	23.5	20.7	89.0	93.1	65.4	35.1	1.4	1.2	2.0	2.2
Mean	3998.2	4747.1	3445.4	3478.2	28.01	26.77	28.39	30.35	54.4	73.4	43.6	39.9	2.0	1.7	2.3	2.0
SD	1537.1	1556.2	1116.5	1008.6	4.49	3.69	4.67	5.45	24.6	26.1	16.8	15.3	0.9	0.4	1.3	0.5

In 2015, N-6 and N-7 were connected together to form split-pond system. N-7 had neither PLs nor feed.

Ponds N-13 and N-14 were newly constructed in 2014.

Table 4.5 Correlation coefficients (*r*) and *p*-values (*p*) of *L. vannamei* weight gain, final weight, final survival rate, and the crop duration with some water temperature variables such as: average of hourly water temperature, coefficient of variance (CV) of hourly water temperature, the count of hours out of the best zone (out of 26 – 28°C), the count of hours out of the optimum zone (out of 23 – 30°C), and the count of hours that fell into tolerated temperature range (15-23 and 30-33°C). The correlation analyses were performed for crop duration data during 2012 (N= 17), 2013 (N= 15), 2015 (N= 13), and the 3 years together (N= 45).

		Weight gain (g/week)				**Final weight (g)**				**Survival rate (%)**				**Crop duration (days)**			
		2012	**2013**	**2015**	**3 years**	**2012**	**2013**	**2015**	**3 years**	**2012**	**2013**	**2015**	**3 years**	**2012**	**2013**	**2015**	**3 years**
Average water temperature	*r*	0.70*	0.85*	0.31	0.59*	0.36	0.32	-0.19	0.15	-0.57*	-0.26	-0.73	-0.05	-0.82*	-0.84*	-0.85	-0.82*
	p	0.0075	0.0016	0.6359	0.0011	0.2771	0.4585	0.7163	0.5088	0.0485	0.5088	0.1767	0.6716	0.0008	0.0019	0.0624	0.0008
CV of water temperature	*r*	-0.78*	-0.81*	-0.39	-0.49*	-0.60*	-0.40	-0.09	-0.18	0.59*	0.39	0.88*	0.50*	0.73*	0.86*	0.58	0.61*
	p	0.0021	0.0051	0.4811	0.0073	0.0245	0.1973	0.7740	0.3611	0.0245	0.1973	0.0358	0.0073	0.0036	0.0021	0.2853	0.0016
Out of best	*r*	-0.83*	-0.83*	-0.37	-0.68*	-0.52	-0.58*	-0.16	-0.26	0.80*	0.73*	0.82	0.62*	0.93*	0.96*	0.77	0.83*
	p	0.0002	0.0002	0.5019	0.0002	0.0578	0.0373	0.6067	0.1597	0.0002	0.0034	0.0632	0.0002	0.0002	0.0002	0.0867	0.0002
Out of optimum	*r*	-0.65*	-0.73*	-0.33	-0.18	-0.60*	-0.58*	-0.29	-0.18	0.66*	0.64*	0.79	0.73*	0.56*	0.67*	-0.0004	0.07
	p	0.0180	0.0176	0.5957	0.4118	0.0331	0.0421	0.4118	0.4118	0.0180	0.0280	0.1008	0.0016	0.0364	0.0189	0.9993	0.7330
Tolerated range	*r*	-0.74*	-0.76*	-0.41	-0.51*	-0.66*	-0.59*	-0.15	-0.29	0.73*	0.66*	0.90*	0.34	0.65*	0.71*	0.42	0.34*
	p	0.0072	0.0156	0.4532	0.0096	0.0147	0.0319	0.7737	0.0689	0.0072	0.0156	0.0267	0.0651	0.0147	0.0128	0.4532	0.0319

p-values were adjusted to control the false discovery rate (FDR) using the Benjamini-Hochberg procedure.
* Significant at $p \leq 0.05$.

Table 4.6 Correlation coefficients (*r*), and *p*-values of pond depth and surface area: volume ratio (SA:V) with shrimp performance variables (N = 52) such as: average final weight (g) of the harvested shrimp (W_f), final survival rate (Sr_f), absolute weight gain of shrimp that was calculated at the end of growing season (WG_f), feed conversion ratio (FCR), and shrimp yield; and with some water temperature variables (N = 45) such as: average of hourly water temperature, coefficient of variance (CV) of hourly water temperature, the count of hours that fell into the following temperature zones: best, optimum, tolerated and extreme.

	Pond Depth		**SA:V**	
	r	***p*-value**	***r***	***p*-value**
W_f	-0.17	0.8935	0.18	0.9446
Sr_f	-0.07	0.8935	0.06	0.9446
WG_f	-0.14	0.8935	0.14	0.9446
FCR	-0.03	0.8935	0.01	0.9446
Shrimp yield	-0.02	0.8935	0.03	0.9446
Average water temperature	-0.12	0.8935	0.08	0.9446
CV of water temperature	0.08	0.8935	-0.06	0.9446
Range of water temperature	0.05	0.8935	-0.05	0.9446
***SD* of water temperature**	0.08	0.8935	-0.06	0.9446
Best temperature zone	-0.03	0.8935	0.06	0.9446
Optimum temperature zone	0.06	0.8935	-0.03	0.9446
Tolerated temperature zone	0.02	0.8935	-0.02	0.9446
Extreme temperature zone	0.11	0.8935	-0.13	0.9446

p-values were adjusted to control the false discovery rate (FDR) using the Benjamini-Hochberg procedure.

Table 4.7 Correlation coefficients (*r*), *p*-values of the weekly estimated survival rate (Sr_w) and weekly average weight of shrimp (W_w) of *L. vannamei* with weekly average, range, maximum, and sum of water temperature in individual ponds; the count of hours that fell into some temperature zones; and the count of hours that fell into some narrow temperature ranges.

	Sr_w (N = 629)		**W_w** (N= 630)	
	r	***p*-value**	***r***	***p*-value**
Average water temperature	0.05	0.1712	-0.13*	0.0016
Range of water temperature	0.12*	0.0008	-0.17*	0.0003
Maximum water temperature	0.15*	0.0002	-0.22*	0.0003
Sum of water temperature	0.19*	0.0002	-0.28*	0.0003
Best temperature zone	0.13*	0.0016	-0.13*	0.0017
Optimum temperature zone	0.10*	0.0045	-0.13*	0.0003
17.5 – 18°C	-0.13*	0.0015	0.13*	0.0017
18 – 18.5°C	-0.16*	0.0002	0.13*	0.0012
18.5 – 19°C	-0.14*	0.0008	0.12*	0.0025
19 – 19.5°C	-0.18*	0.0002	0.15*	0.0004
19.5 – 20°C	-0.16*	0.0002	0.13*	0.0012
20 – 20.5°C	-0.13*	0.0011	0.14*	0.0011
27 – 27.5°C	0.15*	0.0002	-0.17*	0.0003
27.5 – 28°C	0.17*	0.0002	-0.20*	0.0003
28 – 28.5°C	0.07	0.0536	-0.13*	0.0016

p-values were adjusted to control the false discovery rate (FDR) using the Benjamini-Hochberg procedure.
* Significant at $p \leq 0.05$.

Table 4.8 Correlation coefficients (*r*), *p*-values of the weekly relative growth rate (Gr$_{\text{w}}$) and weekly absolute weight gain (WG$_{\text{w}}$) of *L. vannamei* with weekly average, range, coefficient of variance (CV), standard deviation (*SD*), maximum, and sum of water temperature in individual ponds; the count of hours that fell into some temperature zones; and the count of hours that fell into some narrow temperature ranges.

	Gr$_{\text{w}}$ (N= 616)		**WG$_{\text{w}}$** (N= 616)	
	r	***p*-value**	***r***	***p*-value**
Average water temperature	-0.20*	0.0002	0.29*	0.0002
Range of water temperature	0.46*	0.0002	-0.10*	0.0039
CV of water temperature	0.28*	0.0002	-0.11*	0.0015
***SD* of water temperature**	0.26*	0.0002	-0.06	0.1128
Maximum water temperature	0.06	0.1290	0.29*	0.0002
Sum of water temperature	0.12*	0.0037	0.06	0.1299
Best temperature zone	0.29*	0.0002	-0.18*	0.0002
Optimum temperature zone	0.23*	0.0002	-0.19*	0.0002
Out of best temperature zone	-0.16*	0.0002	0.15*	0.0005
Out of optimum temperature zone	-0.17*	0.0002	0.18*	0.0002
Tolerated temperature zone	-0.17*	0.0002	0.20*	0.0002
24 – 24.5°C	0.06	0.1376	-0.16*	0.0002
24.5 – 25°C	0.04	0.3643	-0.22*	0.0002
25 – 25.5°C	0.04	0.3221	-0.24*	0.0002
25.5 – 26°C	0.06	0.1376	-0.25*	0.0002
26 – 26.5°C	0.12*	0.0048	-0.21*	0.0002
26.5 – 27°C	0.32*	0.0002	-0.15*	0.0005
27 – 27.5°C	0.32*	0.0002	-0.14*	0.0011
27.5 – 28°C	0.18*	0.0002	-0.10*	0.0132
28 – 28.5°C	0.11*	0.0124	-0.05	0.1882
30 – 30.5°C	-0.10*	0.0186	0.15*	0.0004
30.5 – 31°C	-0.13*	0.0025	0.17*	0.0002
31 – 31.5°C	-0.16*	0.0002	0.16*	0.0002
31.5 – 32°C	-0.13*	0.0017	0.15*	0.0004
32 – 32.5°C	-0.11*	0.0069	0.13*	0.0017
32.5 – 33°C	-0.09*	0.0246	0.14*	0.0011
Above 33°C	-0.07	0.0784	0.11*	0.0066

p-values were adjusted to control the false discovery rate (FDR) using the Benjamini-Hochberg procedure.
* Significant at $p \leq 0.05$.

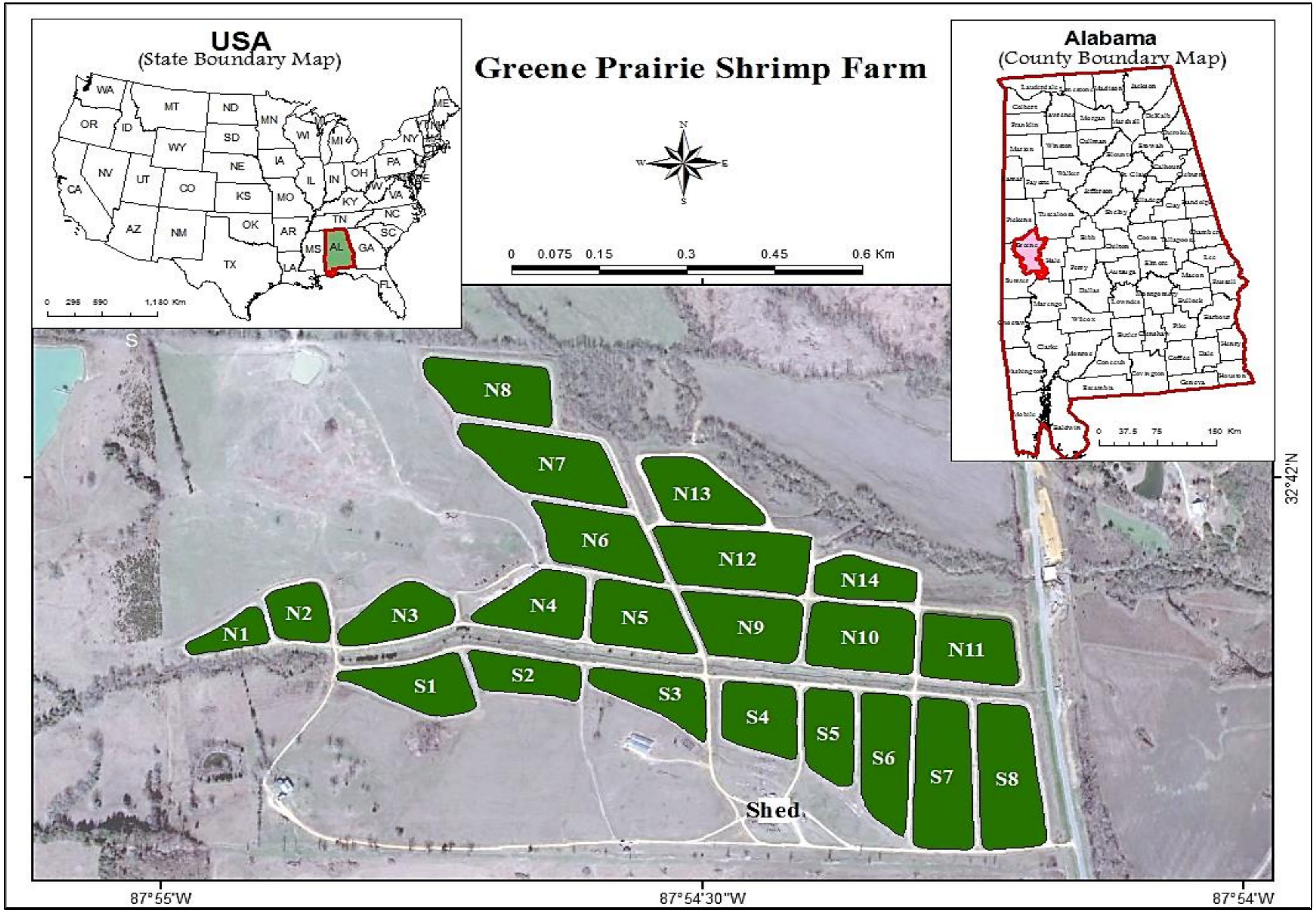

Figure 4.1 Location map of the study farm

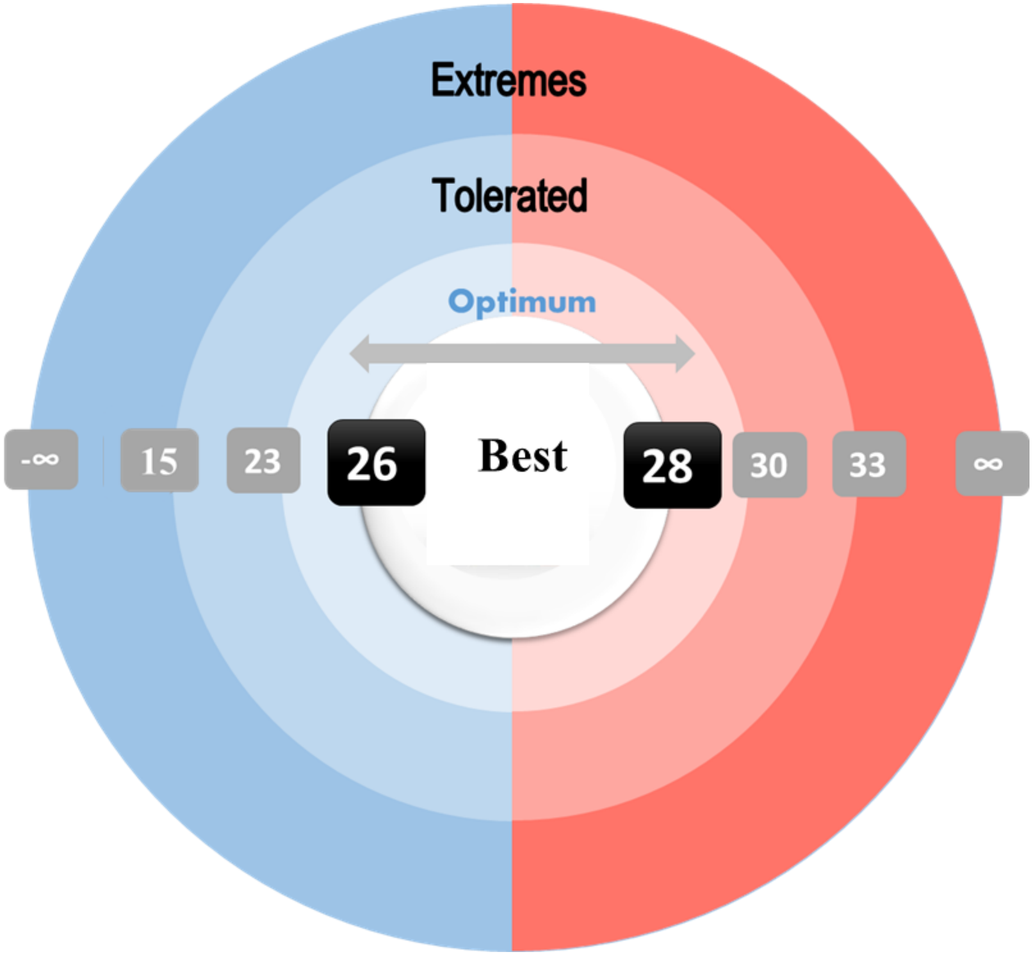

Figure 4.2 Diagram of the four temperature zones. The best zone represents the count of the hours when water temperature falls between 26 and 28°C, the optimum zone represents the count of the hours when water temperature is between 23 and 30°C, the tolerated zone represents the count of the hours when water temperature ranges from 15 to less than 23°C or ranges from more than 30°C to less than 33°C, and the extreme zone represents the count of the hours when water temperature is less than 15°C or higher than 33°C.

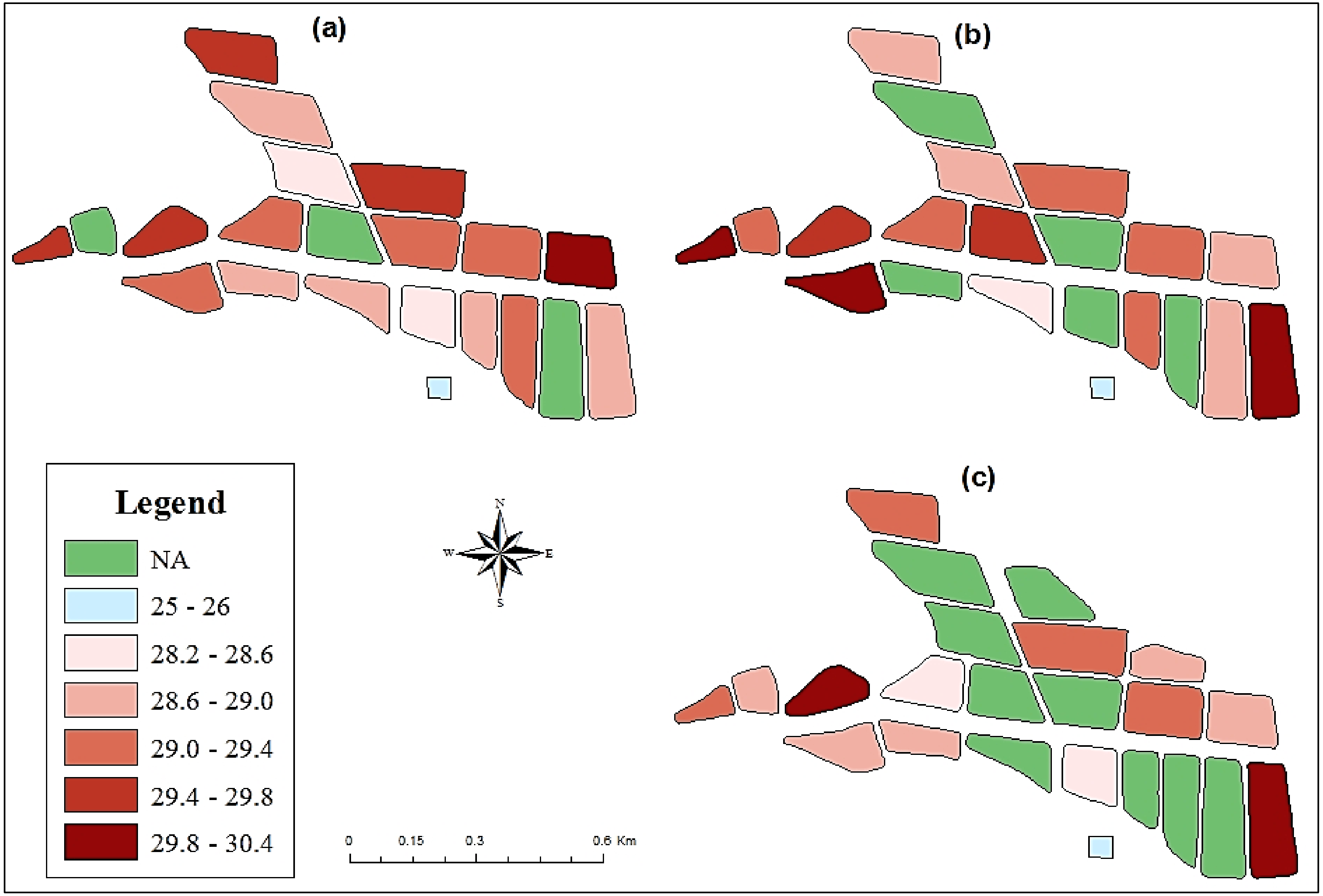

Figure 4.3 Map of the study farm showing the average water temperature (°C) in each pond and air temperature (°C) under the shed during the (a) 2012, (b) 2013, and (c) 2015 growing seasons. NA represents ponds without available temperature data.

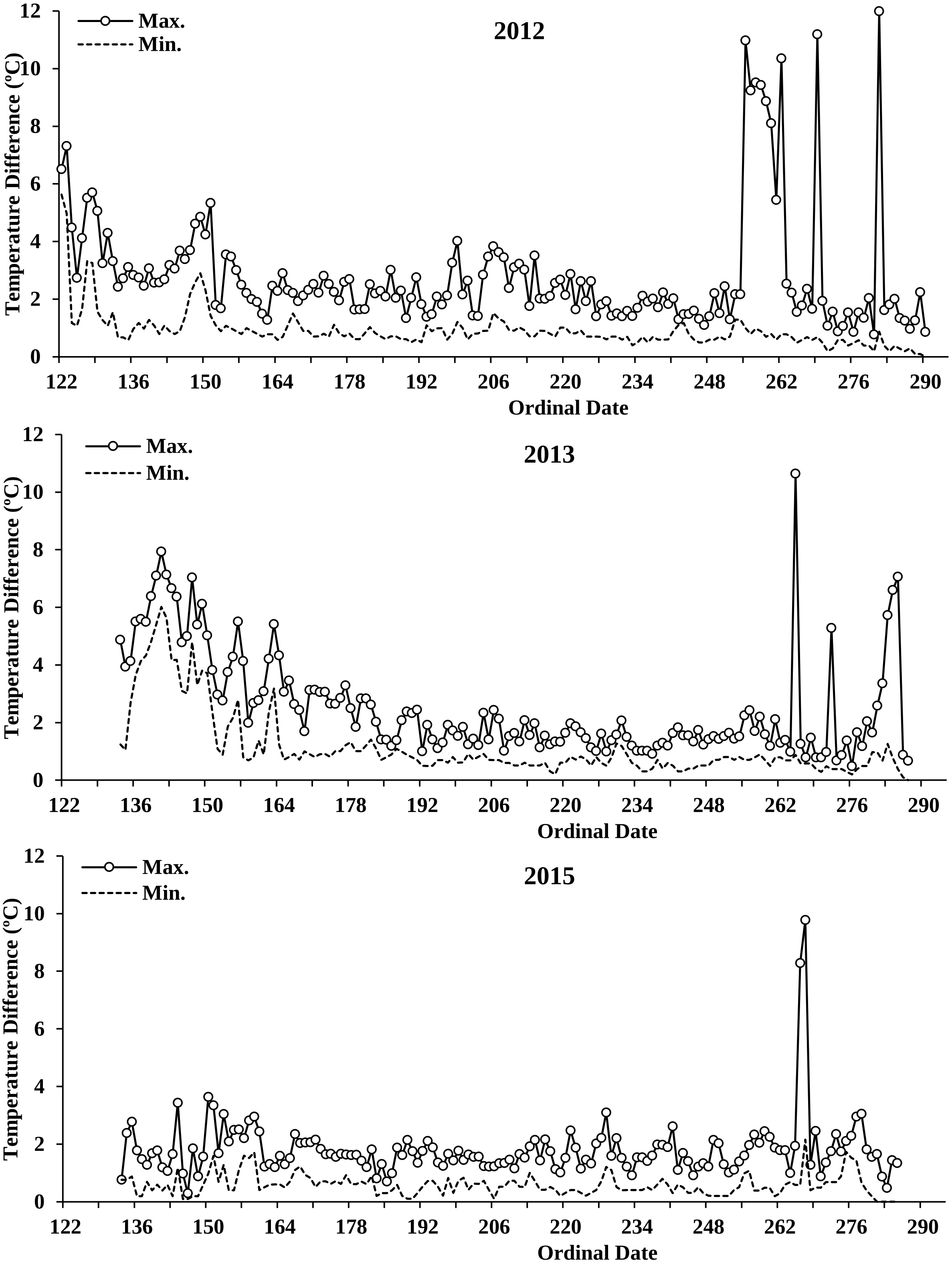

Figure 4.4 Daily maximum and minimum differences in hourly water temperature among shrimp ponds during the 2012 (top); 2013 (middle) and 2015 (bottom) growing seasons.

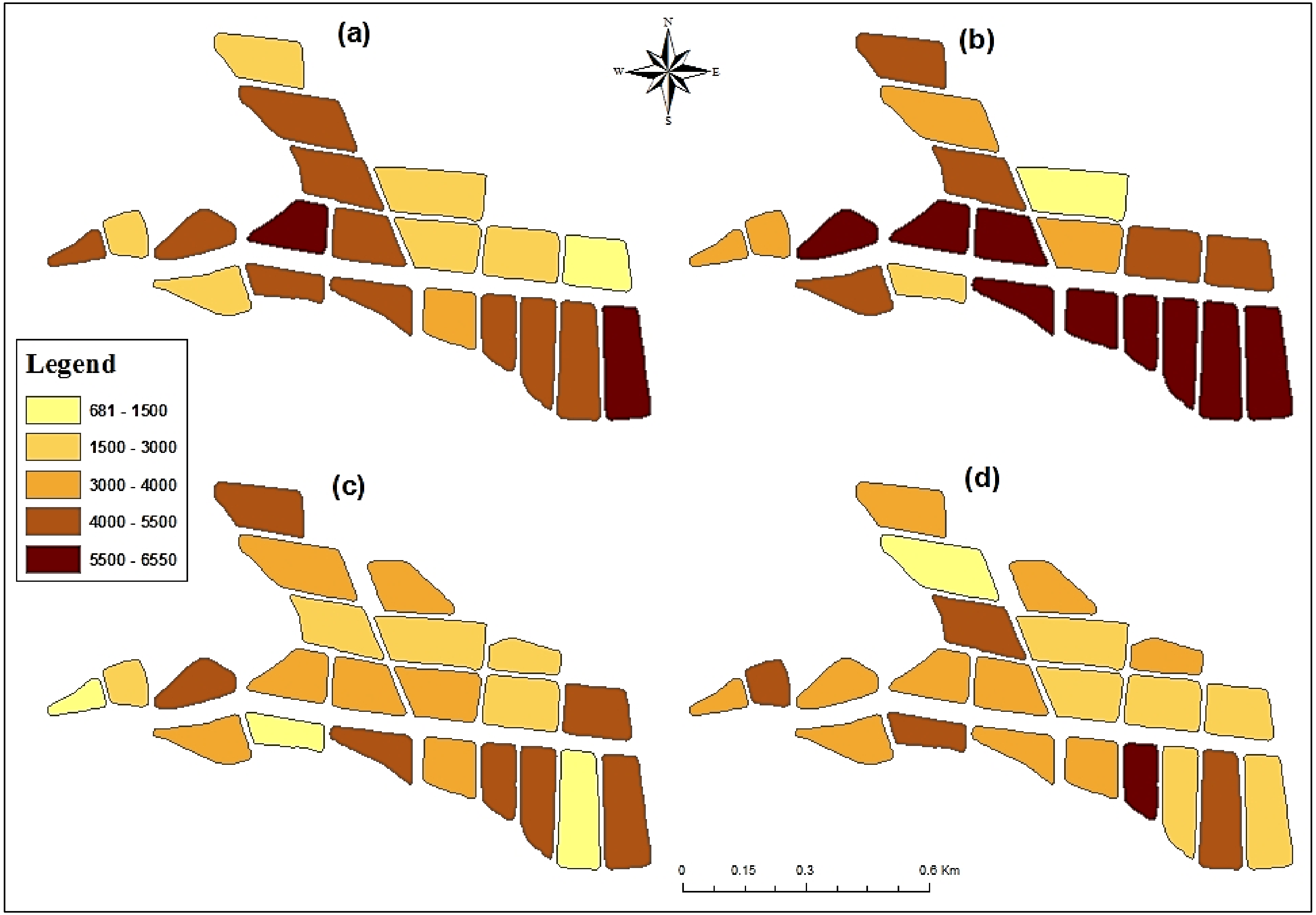

Figure 4.5 Map of the study farm showing the shrimp production in each pond (Kg/ha) during the (a) 2012, (b) 2013, (c) 2014 and (d) 2015 growing seasons.