I. GENERAL INTRODUCTION

Australia has a wide range of climates, from cold-temperate to hot-humid. Most of the pig production units are located outside the tropical zone, at latitudes of from 20 to 35° S. On a world wide basis one third of all pigs are to be found in the tropics where individuals of this species are under almost constant thermal stress (Steinbach, 1978).

Pigs, because of their morphological characteristics, are relatively intolerant of the warmth. They have poor superficial body insulation to protect themselves from solar radiation. They have only a sparse covering of hair, very little loose skin to enhance radiative heat loss, and active sweat glands are confined to their snout (Frazer, 1974). Other glands are plugged with keratin (Ingram, 1967) and are thus of no use.

Under hot conditions various measures may be taken to assist the pig to maintain thermostability. Changes in diets and management can help to achieve maximum growth. The problem of heat stress occurs in growing pigs (Ingram, 1964a; 1964b; Roller and Goldman, 1969) as well as in mature, heavy animals (Mount, 1968).

The levels of dietary energy and protein, energy sources (carbohydrates and lipids), and water usage (temperature of drinking water and water for sprinkling) are not only important factors in pig production; they may also be important ways to ameliorate heat stress.

The present study had three main objectives: firstly, to determine the effect of different environments on the growth performance of pigs under commercial situations in the eastern states of Australia. Secondly, to investigate means of alleviating the problem of heat stress by nutritional manipulation and management, and thirdly to determine the effects of high temperature on nitrogen retention and energy metabolism in growing-finishing pigs.

Before proceeding to the experimental section, a general review of literature covering the relevant areas will be presented. Throughout this thesis all original measurements cited have been converted where necessary to the metric system.

II. LITERATURE REVIEW

1.0 THE IMPACT OF HOT CLIMATES ON PIG PRODUCTION

The critical temperature may be defined as the lowest air temperature at which heat loss is minimal (Close, Heavens and Brown, 1981). The critical temperature can be further classified into lower and upper critical temperatures, below or above which the animal is compelled to increase extra-thermoregulatory activities to maintain normal body temperature. If ambient temperature exceeds the upper critical temperature then the pig starts to suffer "heat stress". Therefore, it is of economic importance to maintain pigs in an environment between these two temperatures; this temperature range is the pig's thermoneutral zone (Boon, 1981).

Lee (1965) defines "stress" as the magnitude of forces external to the bodily system which tend to displace that system from its ground state. "Strain", on the other hand, is the internal displacement from the ground state brought about by the application of a stress.

Optimum pig production often depends upon the ability of the pigs to maintain statisfactory levels of those physiological activities essential for survival and growth in the face of adverse conditions. In hot climates, the degree of heat stress experienced by growing and finishing pigs is principally determined by the combined effects of ambient temperature, humidity and wind velocity. This is particularly true when pigs are housed under intensive conditions and the potentially large influence of solar radiation is removed from their immediate environment.

The strain caused by climatic elements, especially heat, is reflected in changes in a number of physiological reactions within the body as the pig attempts to maintain homeothermy. The loss of production which occurs in hot climates is primarily due to a reduction in feed intake and subsequently growth rate (Heitman and Hughes, 1949; Bond, Kelly and Heitman, 1952; Mangold, Hazen, Hays and Speer, 1960; Hale and Johnson, 1970; Morrison and Mount, 1971; Tonks, Smith and Bruce, 1972; Straub, Weniger, Tawfik and Steinhauf, 1976). Subsidiary changes in type of growth (Fuller, 1965; Pearson, Reineke, Hoefer and Morrow, 1966; Hale, Johnson and Warren, 1968; Weaver and Ingram, 1969; Sugahara, Baker, Harmon and Jensen, 1970), in the size of internal organs (Sugahara *et al.*, 1970; Holmes, 1971b; Straub *et al.*, 1976), in metabolic rate (Marple, Jones, Alliston and Forrest, 1974; Lynch, 1978; Close, Heavens and Brown, 1981), and in fertility (Signoret, 1980) have been recognised. In very severe cases death may result from heat stress (Marple *et al.*, 1974).

There is the need for a new technology of pig production to be developed in order to increase production in hot climates. One part of this technology will relate to the ability of pigs to withstand the strain which results from heat stress; another part, the subject of this thesis, involves various means of reducing the level of heat stress experienced by pigs.

2.0 FACTORS AFFECTING HEAT STRESS IN PIGS

There will always be an outflow of energy from a body which has a higher temperature than its immediate surroundings. The rate of loss of heat depends on the gradient between these two temperatures and the nature of the media through which the heat must travel (Callen, 1960; Fong, 1976). Therefore, factors that affect the rate of heat exchange between the pig and its environment will effect the magnitude of the strain caused by that heat stress.

2.1 Anatomical and Physiological Factors

Pigs, because of their morphological characteristics, are intolerant of hot climates (Frazer, 1974). Under extensive conditions where they are subjected to solar radiation, the sparse hair covering may protect the pigs from the solar radiation to a limited extent (Kelly, Bond and Heitman, 1954). A pigmented skin also probably protects against the harmful effects of ultraviolet radiation (sunburn), although it certainly results also in a greater absorption of heat (Kelly, Bond and Heitman, 1954).

There are two avenues by which domestic animals can utilize evaporative cooling as a way of dissipating heat from their bodies; cutaneous and respiratory evaporative cooling. In the pig it has been found that cutaneous evaporation is relatively small when compared to that in other domestic animals. Morrison, Bond and Heitman (1967) found, for example, that the cutaneous evaporation from 90 kg Duroc gilts represented between 35 and 67% (20.9-30.0 g/m^2/h) of total evaporation at 29°C ambient temperature. In calves exposed to 27°C ambient temperature (Kibler and Yeck, 1959) the corresponding range was 64 to 80% (40-160 g/m^2/h). The amount of cutaneous evaporation recorded in pigs could have arisen largely from diffusion of water through the skin, since active sweat glands in this species are confined to the snout (Frazer, 1974). More details of the importance of cutaneous evaporation in pigs will be given when discussing water utilization (see II-5.0).

Respiratory evaporative cooling thus remains the only other avenue for the pig to maintain homeothermy at high temperatures. The first reaction of pigs when exposed to hot climates is to increase respiration rate. Morrison, Bond and Heitman (1967) found that the mean respiration rate of 90 kg gilts increased eightfold when the ambient temperature was increased from 15°C to 29°C at the same relative humidity (70%). There was a corresponding threefold increase in respiratory evaporative loss.

Hyperventilation could be expected to bring about changes in blood acid-base balance. Exposure of pigs to heat stress has been found to lower blood pH and pO_2, and to elevate blood pCO_2 and lactic acid levels (Forrest, Will, Schmidt, Judge and Briskey, 1968; Topel, 1969). Thus respiratory alkalosis is likely to accompany heat stress and as long as this respiratory alkalosis persists the pig will primarily utilize aerobic pathways of energy metabolism (Aberle, Merkel, Forrest and Alliston, 1974). The extent to which evaporative cooling relieves heat stress depends on the severity of the climatic factors (see II-2.2.2) to which the pig is exposed.

2.2 Climatic Factors

Ambient temperature, humidity and wind velocity under housed conditions, in addition to solar radiation under extensive conditions, are the major climatic elements that influence thermostability in pigs. They affect heat stress directly by way of heat load and indirectly by interference with the efficiency of heat loss.

2.2.1 **Ambient temperature**

The degree of heat stress experienced by pigs increases with increasing ambient temperature. Marple *et al.* (1974) subjected four gilts (65-70 kg), under general anaesthesia, to ambient temperature which was increased at the rate of 5° C/h from 27° C until they eventually succumbed to the effects of extreme heat stress. The rectal temperatures of these pigs increased significantly during exposure to high ambient temperatures. Marple *et al.* (1974) also observed that the 60 minute period ante-mortem was characterised by the most rapid increase in body temperature. The authors suggested that this rise resulted from a deterioration of cooling mechanisms as a result of the combined environmental and metabolic heat loads. During the later stages of heat stress, temperature regulation was suggested to be further complicated by accelerating the rate of energy metabolism due to the van't Hoff effect. Death occurred in all four pigs when their rectal temperature reached approximately 43° C.

Growing and finishing pigs do not tolerate high temperature as well as younger pigs. This is due largely to the fact that the rate of heat loss declines per unit of liveweight as pigs become heavier (Holmes and Mount, 1967). Holmes (1968) found that at 20° C the heat loss of pigs weighing 26 to 64 kg liveweight was proportional to $W^{0.6}$, where W was liveweight in kg. When the ambient temperature was increased to 30° C, the total heat loss was found to be smaller, although the decrease was significant for the heavier pigs only, presumably due to the greater heat stress experienced by them.

There are some discrepancies in the literature that relate to the optimum temperature for growth in pigs, especially in the 45 to 90 kg weight range. Morrison, Bond and Heitman (1968a) suggested 22° C at 50% relative humidity whereas Hazen and Mangold (1960) suggested 19° C at 55% relative humidity and Cunha (1977) gave a value of 18° C. It is unlikely that a precise temperature can be identified and Heitman, Kelly and Bond (1958) and Mangold *et al.* (1960) found that the best performance of growing pigs was obtained when ambient temperature was maintained between 16 and 21° C.

2.2.2 **Humidity**

It has already been established (see II-2.2.1) that evaporative cooling is an important heat dissipating mechanism in pigs. In relatively hairless animals cutaneous evaporation is particularly effective since the evaporating water takes up heat directly from the skin (Morrison, Heitman, Givens and Bond, 1972). In the case of respiratory evaporation, heat is taken up from the moist membranes of the upper respiratory tract. An increase in relative humidity at any one temperature leads to a decrease in the water-carrying capacity of the air and thus to a reduced rate of evaporation. By calculating the total evaporative rate of the pigs studied by Morrison, Bond and Heitman (1967) at 29° C and using the value of latent heat of water given by Holmes and Close (1977), the mean total evaporative heat losses from 90 kg gilts were found to be 3.97, 4.27, 4.10 and 3.10 kJ/pig/h at relative humidities of 30, 50, 70 and 90% respectively. It appears from these calculations that high humidity has a marked suppressing effect on evaporative cooling in the pig.

Heitman and Hughes (1949) reported that for pigs weighing over about 90 kg, there was not much difference in response when they were exposed to relative humidity of 30 and 94% at 32° C ambient temperature. When the air temperature was increased to 36° C at 30% relative humidity the pigs lost weight but survived for a prolonged period. Furthermore when pigs were subjected to 36° C and to a relative humidity which rose from 30 to 94% over an eight hour period, Heitman and Hughes (1949) observed that their respiration rate doubled and body temperature increased by 1.4° C.

2.2.3 **Solar radiation**

Under modern day pig production systems where pigs are housed intensively, solar radiation is the least important climatic factor contributing to heat stress. Under extensive conditions where pigs are subjected to solar radiation, the solar rays can directly increase the pig's heat load. Upon striking a surface such as pig skin, solar radiation is converted to heat energy (Blum, 1945; Stewart, 1953; Sapford, 1957; Fong, 1976). The solar heat load, if taken at face value, can be many times the magnitude of an animal's basal heat production.

Pigmented skin will enhance the absorption of radiant heat since black bodies tend to absorb heat better than white ones (Fong, 1976). It is well documented in cattle that pigmented skin offers some protection from skin cancer (Yeates, Edey and Hill, 1975) and that solar rays stimulate sweat gland activity (Murray, 1966; Moran, 1973). It is also commonly reported by farmers that white pigs experience sunburn quicker than black pigs.

2.2.4 **Wind velocity**

High wind velocity at temperatures both above and below the thermoneutral zone may produce adverse effects on pigs in terms of increased heat dissipation. Mount, Start and Brown (1980) exposed growing pigs, about 23 kg liveweight, to ambient temperatures of 8, 12, 16 or 20° C under conditions of no air movement and found no significant differences in growth performance. However, when the wind velocity was increased to 0.80 m/s, weight gains of the pigs at constant energy intake were reduced at 12° C. This was probably due to the fact that wind velocity affected the maintenance energy requirement of the pigs. Close, Heavens and Brown (1981) found that when wind velocity increased from 0.03 to 0.56 m/s, the individual pig's (20-31.8 kg liveweight) maintenance energy requirement was increased by 176, 225 and 108 $kJ/kg^{0.75}/d$ from base levels of 706, 490 and 517 $kJ/kg^{0.75}/d$ at 10, 20 and 30° C, respectively. Presumably the lesser (25%) change at 10° C than at 20° C (46%) was a reflection of peripheral vasoconstriction and lower skin temperature.

Morrison, Givens and Heitman (1976) found that at a wind velocity of 0.50 m/s pigs performed better than they did at 0.05 m/s. A wind velocity of 1.00 m/s was found to produce intermediate results in pigs weighing 36 to 86 kg at 27 to 35° C ambient temperature. Data from Bond, Kelly and Heitman (1952) were used by Morrison, Givens and Heitman (1976) to estimate the effect of wind velocity on heat loss from pigs. They found convective heat loss to be about 33 and 24% of total heat loss at 28 and 34° C, respectively.

The evaporation rate can also be increased by increases in wind velocity, which in practice not only remove greater quantities of moisture-laden air but also create greater fluctuations in humidity close to the skin surface. Therefore, increased wind velocity is potentially a means of increasing heat loss by both the evaporative and convective routes (Bond, Kelly and Heitman, 1958; Wahlstrom, 1981).

2.2.5 **Diurnal variation in temperature and humidity**

Under natural conditions there is a diurnal variation in temperature and humidity. Ambient temperatures tend to reach maxima in mid-afternoon and minima in early morning, while humidity tends to fluctuate inversely with the temperature.

Since marked variations in climatic elements exist, it follows that the strain imposed by heat stress will also exhibit a diurnal variation. Steinbach (1978) reported that the respiration rate of pigs was lowest at about midnight (20-30 breaths/min) and highest at mid-afternoon (70 b/min). Andrews and Noffsinger (1956) found that under normal conditions of diurnal variations, daytime temperatures of 32°c and above resulted in respiration rates of 150 to 200 b/min (compared to rates of 20-40 b/min at 16 to 21°c). Holmes and Mount (1967) reported that there were also diurnal fluctuations in the rate of heat loss, with maximum values in the late evening and minimum ones early in the morning. The amplitude of the diurnal cycle was ±15% of the mean rate of heat loss (Cairnie and Pullar, 1959; Holmes and Mount, 1967).

Prediction of pig performance from data collected at constant temperatures (e.g. Morrison, Hahn and Bond, 1970) may not always be directly applicable to practical situations, especially where the amplitude of the diurnal temperature variation is more than about 10° C. However, where an amplitude of only about 5° C occurs, the reduction in performance may not be as large as when pigs experience a constant temperature equivalent to the mean of the variable one. In fact, it may be beneficial (Morrison, Heitman and Givens, 1975). Apparently the cool night temperature allowed a compensatory physiological adjustment to take place (Andrews and Noffsinger, 1956).

2.3 Nutritional Factors

An animal requires energy for its organs to function. The extent of this energy requirement varies with activity and age of the animal (Blaxter, 1969). The source of this energy is the animal's diet and different types of diets may produce different amounts of energy. A pig maintains a relatively stable body temperature of about 38.5 to 40° C. Its body temperature will be higher when exercised, or after eating (Lynch, 1978) due to an increase in metabolic rate. In a hot climate, heat production is also increased due to the increase in metabolic rate as a result of energy expended in operating cooling mechanisms (Stahly, 1982). In extreme cases of heat stress, the rate of increase in heat production may be further accelerated by the van't Hoff effect (Marple *et al.*, 1974). The general effects of a heat load were demonstrated in a study on chicks starved for 24, 48 and 72 hours at a high temperature by McCormick, Gahlich and Eden (1979). The survival time of the 48 and 72 hour starved chicks was found to be more than double that of the fed chicks.

Early studies (Forbes and Swift, 1944; Forbes, Swift, Elliott and

James, 1946; Swift and Black, 1949) revealed that heat increment is variable for different dietary nutrients but is generally low for fat and carbohydrate, and higher for protein. Much later studies (Ewan, 1979; Just, 1980; Taylor and Fischer, 1980) indicated that diets with fibrous feedstuffs have high heat increments.

The temperature of feed or water, which is usually lower than that of the pig's body, may be utilized to reduce heat stress. The amount of heat required to warm, to body temperature, any water or feed ingested by an animal is usually small in relation to the animal's total heat loss (Blaxter, 1969). Nevertheless, as Blaxter observed, there are exceptions to this. Results from studies with pigs (Holmes, 1970) indicated that after ingestion of cool whey, there was indeed a general fall in deep body temperature. Shivering was regularly induced at 16° C and occasionally even at 28° C ambient temperature. Vasoconstriction was also induced at 28° C and 33° C and a reduction in respiratory rate occurred at 33° C. Similar reactions have been observed in man (Benzinger, 1967), sheep (Webster and Johnson, 1968) and goats (Andersson, Grant and Larsen, 1956) after drinking cold water.

It has been observed that pigs tend to utilize the above "cooling effect" by drinking more water in a hot climate. Steinbach (1978) found that more water was ingested by pigs in the afternoon and less at night. Heitman and Hughes (1949) found that when pigs (34 to 57 kg) were exposed to 21, 32 and 38° C they drank 136, 160 and 273 ml/pig/h respectively.

3.0 EFFECTS OF A HOT CLIMATE ON THE GROWTH PERFORMANCE OF PIGS

Growth performance may include various factors that bring about net gain or deficit in terms of weight gain and feed efficiency, excluding those resulting from breeding practice. Feed comprises 75 to 85% of the cost of producing a pig when fed *ad libitum* (Wyllie, Morton and Owen, 1979). It is therefore important to know the extent to which climate can affect intake and growth performance.

3.1 Voluntary Feed Intake and Daily Rate of Gain

It is accepted that pigs eat to satisfy an energy requirement and that voluntary feed intake increases as body weight increases (Stahly, 1982). However, climatic conditions can influence energy intake and therefore the rate of weight gain (Heitman and Hughes, 1949; Bond, Kelly and Heitman, 1952; Mangold, Hazen and Hays, 1967).

There are numerous reports (Hale, Johnson and Warren, 1968; Teague, Roller and Grifo, 1968; Todd and Daniels, 1968; Hale and Johnson, 1970; Morrison and Mount, 1971; Tonks, Smith and Bruce, 1972; Peng and Heitman, 1974; Morrison, Heitman and Givens, 1975; Straub *et al.*, 1976; Lynch, 1977) that pigs reduce their voluntary feed intake when exposed to a hot climate. This is due to an apparent effort by the pigs to lower their heat production (Lynch, 1978) and hence to reduce the physiological burden of dissipating excess body heat (Stahly, 1982). This reduction in energy intake results in a lower daily rate of gain.

Hale, Johnson and Warren (1968) reported that the voluntary feed intake of pigs in summer (2.58 kg/pig/d) was significantly less than that in winter (2.83 kg/pig/d). Teague, Roller and Grifo (1968) reported an average daily feed intake by gilts weighing 117 kg at 27° C of 2.27 kg/pig/d; this was higher (by 21%) than that of the treatment group held at 33° C. In heavy sows (210 kg), such as those used by Lynch (1977), voluntary feed intake was depressed even under mild heat stress (4.58 and 5.23 kg/pig/d at 27 and 21° C respectively).

Although the work of Hale, Johnson and Warren (1968), and Hale and Johnson (1970) showed no statistically significant differences in daily rate of gain, despite a significantly lower voluntary feed intake in summer than in winter, daily rate of gain was found to be six percent lower in summer than in winter. Furthermore, Todd and Daniels (1968) reported that pigs grown from 20 to 89 kg during summer in a simple, uninsulated iron shelter gained 11% slower (558 vs 630 g/d) than comparable animals in partly insulated pens.

Morrison, Heitman and Givens (1975) also observed a significant depression in voluntary feed intake and daily rate of gain when pigs were subjected to 6° C above optimum temperature. At optimum ambient temperature and optimum + 6° C the daily intakes were 2.49 and 2.01 kg/pig/d, and the daily rates of gain were 720 and 600 g/d respectively.

3.2 Feed Efficiency

There are discrepancies in the literature (Hale, Johnson and Warren, 1968; Morrison, Bond and Heitman, 1968a; Seymour, Speer and Hays, 1968; Todd and Daniels, 1968; Straub *et al.*, 1976) as to whether feed efficiency is influenced by climate. These differences may have arisen through different climatic conditions and feed type used for comparison of feed efficiency between the different workers. Nevertheless, judging from the effect of climate on energy metabolism (see II-2.0), it would be anticipated that feed would be utilized less efficiently when pigs are living in above optimum rather than optimum temperatures because of the metabolic costs of heat dissipation and the fact that efficiency and intake are inversely related.

3.3 Dressing Percentage

A hot environment seems to have little effect on dressing percentage. Smith and Tonks (1966) found that pigs (22-90 kg) raised in a hot environment (28° C) had the same dressing percentage as those at 21° C. Hale and Johnson (1970) and Seerley, McDaniel and McCampbell (1978) reported that there was no difference in dressing percentage due to season (summer and winter). Nevertheless, Todd and Daniels (1968) reported that pigs that grew in an environment of 11-43° C dressed (74.5%) significantly better than those (73.2%) grown in an environment of 13-39° C.

3.4 Anatomical Changes and Backfat Depth

There is detailed evidence that anatomical changes occur in pigs raised in a hot climate such that affected animals develop longer legs and tails, and larger ears, and have a greater blood supply to the skin than pigs raised in a normal environment (Fuller, 1965; Pearson *et al.*, 1966; Hale, Johnson and Warren, 1968; Weaver and Ingram, 1969; Sugahara *et al.*, 1970). High temperatures also induce changes in the weight of the internal organs (Sugahara *et al.*, 1970; Holmes, 1971b). Straub *et al.* (1976) reported reduced weight of heart, liver, kidneys, spleen and stomach of pigs exposed to a high temperature. The lengths of the carcases of pigs grown in a hot climate tend to be greater than those of pigs raised in a cool climate (Stahly and Cromwell, 1979). Bruner and Swiger (1968) reported that pigs that grew through summer had longer ($P<0.01$) carcases than those grown in winter. Todd and Daniels (1968) observed that pigs subjected to an 11-43° C environment had longer carcases than those raised at 13-39° C, although the difference was not statistically significant. Boars raised at 35° C (Straub *et al.*, 1976) were found to be as much as 5.4 cm longer ($P<0.01$) than those raised at 15° C.

Backfat depth is an important characteristic of pigs in terms of market acceptability. At the present time in Australia, for example, carcases having more than 20 mm fat at the P2 position are downgraded and discounted by about 30 cents/kg (Taylor, pers. comm.).

There are some discrepancies among researchers as to whether backfat depth or fatness of the carcases of pigs is affected by a hot climate. Thus reports vary from there having no effects (Seymour, Speer, Hays, Mangold and Hazen, 1964; Smith and Tonks, 1966; MacGrath, van der Noot, Gilbreath and Fisher, 1968; Hale and Johnson, 1970; Tonks, Smith and Bruce, 1972) to either an increase (Houghton, Butterworth, King and Goodyear, 1964; Bruner and Swiger, 1968; Holmes, 1971b) or a decrease (Fuller, 1965; Sugahara *et al.*, 1970; Straub *et al.*, 1976; Stahly and Cromwell, 1979) in carcase fat.

Bruner and Swiger (1968) found that pigs raised in summer yielded carcases with a backfat depth of 3.70 cm, a figure which was significantly greater (by 1.1%) than that in the carcases of pigs raised during winter. Hale and Johnson (1970) reported a similar trend, though in their case the difference was of the order of six percent. On the other hand, Hale, Johnson and Warren (1968) found that pigs in summer (3.38 cm) had less backfat than those raised in winter (3.68 cm) and Straub *et al.* (1976) obtained a reduction in backfat in pigs raised at 35°C (1.50 cm) compared to those raised at 15°C (1.73 cm).

The uncertainty of the effect of a hot climate on the degree of body fatness may have arisen from differences in the severity of the heat stress studied by the various workers or, as pointed out by Farrell (1978), from differences in feeding levels, sex and age of pigs. It must also be recognized that there may be no consistent effect of environmental temperature on backfat depth, in which case the variable results recorded above would only to be expected.

4.0 AMELIORATION OF HEAT STRESS BY NUTRITIONAL MEANS

It has been established in this review (see II-3.0) that the growth of pigs is adversely affected by a hot climate. Broadly, there are two possible ways to ameliorate the effects of heat stress, by changes in either:-

(i) nutrition, or

(ii) management (see II-5.0).

These will be considered next.

4.1 Dietary Protein Levels

A protein deficiency may arise simply through a reduction in voluntary feed intake by pigs in hot climates if the diet provided is not formulated to take account of this possibility. By increasing the concentration of protein in the diet the protein deficiency may be eliminated and an increase in growth under hot conditions may result.

Seerley, Poley and Wahlstrom (1964) reported that the daily rate of gain of pigs (17-95 kg) fed a high protein diet (14.4%) was significantly greater than that of pigs fed a low protein (12.5%) diet, although there were no differences in feed efficiency nor carcase length. Mitchell, Johnson, Hamilton and Haines (1950) indicated that environmental temperature influenced nutrient requirement of young pigs. Agarwala and Sundaresen (1956) observed that pigs fed a high protein diet consumed less feed than those fed low protein diet in summer, with the reverse occurring in winter.

Seymour *et al.* (1964) offered diets with two protein levels (14-20% and 10-16%) to pigs grown from three weeks of age to 91 kg at either of two temperatures (16° C and 32° C). They found that there was no interaction between protein level and environment over the entire experimental period. There was, however, a significant interaction of protein level and temperature on feed efficiency (variation in FCE greater on the high protein diet) for the period from three weeks of age to 50 kg liveweight. Nevertheless, there was a significant increase in daily rate of gain and feed efficiency and a decrease in backfat due to the higher dietary protein level. Hale and Johnson (1970) did not obtain a significant interaction between season and diet for either daily rate of gain or feed efficiency when pigs (27-96 kg) were offered two protein levels (20 to 24% and 10 to 14%). It was pointed out (Hale and Johnson, 1970) that the mean temperatures (26° C - summer; 11° C - winter) in that study were much lower than those used by Seymour *et al.* (1964). Dividich and Canope (1978) fed four levels of dietary protein (12, 16, 20 and 24% DCP) to pigs at 20.5 to 27.5° C. They found that daily rate of gain and feed efficiency were best on the diet with 16% protein to 60 kg liveweight and with 12% protein for the finishing pigs. Dressing percentage and backfat depth were found to decline linearly with increasing level of protein.

4.2 Dietary Energy Levels

The energy concentration of the diet influences the daily energy intake of growing-finishing pigs (Hanahan, 1977). Cole, Duckworth and Holmes (1967) measured voluntary feed intake in pigs (38 to 105 kg) offered diets of different digestible energy levels (calculated to be 12.4, 14.0, 15.2 and 16.3 MJ/kg DM) over four periods; the pigs consumed similar amounts of energy irrespective of the digestible energy content of the diets.

Furthermore, O'Grady (1978) reported that compensation in energy intake reached a maximum at about 13.6 MJ DE/kg. Any further increase in digestible energy concentration resulted in a reduction in daily feed intake (O'Grady and Bowland, 1972) while digestible energy intake was maintained.

The efficiency of energy utilization, expressed as energy retained as a percentage of metabolizable energy, has been shown in pigs to increase linearly as the metabolizable energy content of the diet increases (Just, 1980). Although a diet of approximately 13.8 MJ ME/kg had been shown to be adequate for growth (Seerley, McDaniel and McCampbell, 1978), additional energy was not likely to enhance growth at normal temperatures. An energy density of more than 13.8 MJ ME/kg should be utilized most efficiently by pigs living in a hot climate (Seerley, McDaniel and McCampbell, 1978).

It has been pointed out by Stahly (1982) that since body's physiological need or responses to alteration in body heat production is influenced by environmental temperature, pigs in a hot environment would tend to consume more feed that contained fat which has a low heat increment (Hillcoat and Annison, 1974; Ewan, 1979; Just, 1980).

Several researchers have reported that pigs gain faster and require less feed per unit gain when animal fat is added to the diet (Kropf, Pearson and Wallace, 1954; Heitman, 1956; Sewell, Tarpley and Abernathy, 1958; Brooks and Thomas, 1959; Pond, Kwong and Loosli, 1960; Waterman, Romos, Miller and Leveille, 1973; Seerley, McDaniel and McCampbell, 1978). Other researchers reported a reduction in feed intake on diets high in fat (Boyd, Moser, Peo and Cunningham, 1978; Allee and Salava, 1978; Pollmann, Danielson, Crenshaw and Peo, 1980).

The work of Hale, Johnson and Warren (1968) revealed that pigs offered a diet with eight percent tallow required nine percent less feed per unit gain than those given a diet with only four percent tallow which in turn required seven percent less feed per unit gain than pigs fed the basal diet containing no added tallow.

Stahly and Cromwell (1979) kept growing (27 to 64 kg liveweight) and finishing (68 to 90 kg liveweight) pigs under three different environmental temperatures (10, 22 and 35° C). Diets containing zero (13.5 MJ ME/kg) or + 5% tallow (14.4 MJ ME/kg) were offered to the pigs. In the growing phase (27 to 64 kg liveweight) it was found that there was a significant interaction between dietary fat level and environmental temperature on voluntary feed intake: the addition of tallow to the diet reduced voluntary feed intake and growth rate in pigs at 10° C. However, with finishing pigs (68 to 90 kg liveweight) under similar conditions, it was found that voluntary feed intake, weight gain and feed efficiency responded quadratically as ambient temperature was increased from 10 to 35° C. Optimum performance was recorded at 22° C temperature. There was also a significant interaction between dietary tallow level and environmental temperature on growth rate. Addition of tallow to the diet caused a significant increase in growth rate in pigs housed at 22° C and 35° C only. Feed efficiency was improved at all temperatures for both growing and finishing pigs.

Rice pollard is widely used as a stock feed in tropical regions (Campabadal, Creswell, Wallace and Combs, 1976). A full fat rice pollard may contain up to 22% lipid and up to 17.5 MJ DE/kg DM. Despite the potential of rice pollard as a lipid source, there are very few studies on its effect on pig growth at high temperatures.

Thrasher and Mullins (1965) replaced 0, 20 and 30% of a corn-based diet with rice pollard for growing-finishing pigs and found that both 20 and 30% of rice pollard in the diet reduced gain and feed efficiency. However, it was pointed out (Thrasher and Mullins, 1965) that the reduced performance might have been due to the poor quality of the protein in the diets containing rice pollard. Campabadal *et al.* (1976) found that inclusion of rice pollard, up to 30% in a diet, did not affect the performance of growing-finishing pigs.

5.0 AMELIORATION OF HEAT STRESS IN PIGS BY UTILIZATION OF WATER

It has long been noted by husbandmen that pigs wallow in water or seek wet places when they are hot. This has led to the practice of spraying water over pigs, especially during hot afternoons in tropical countries. Cool water when ingested can act as a heat sink, since it absorbs heat from the pig while being warmed up to body temperature. Water also absorbs as latent heat about 2.6 kJ/g when it evaporates from the respiratory tract or skin surfaces of the pig. This reduces the heat load of the pig.

5.1 Effect of Hot Climates on Cutaneous Evaporative Cooling

Cutaneous evaporation in an animal is a result of two possible processes viz. passive moisture loss by diffusion and active sweating. Cutaneous evaporation in a hot environment is affected by both ambient temperature and humidity. It is most likely that any increase in ambient temperature would result in a reduction in vapour pressure under natural conditions, thus enhancing further evaporation. The site at which evaporation occurs may have a significant effect on the efficiency of cutaneous evaporative cooling. It is most likely that in relatively hairless mammals such as pig and man evaporation occurs at the skin surface and that the cooling influence is then transferred quickly to the skin and the peripheral circulation. On the other hand, in hairy animals such as cattle the site of evaporation is somewhat obscure. It has been suggested that evaporation may occur at the skin and also from hairs very close to their bases (Allen, Bennett, Donegan and Hutchinson, 1970).

The rate of diffusion of water through skin is influenced by the gradient in the partial pressure of moisture between the saturation level at skin temperature and that prevailing in the air. Thus, with skin temperature rising in the heat, there is an increase in water loss. However, in both man and cattle, for example, the amount of heat lost via the diffusion pathway is very small when compared with that lost by sweating (Bianca, 1968).

Although the pig does possess apocrine sweat glands (Montagna and Yun, 1964), their number is much less than that found in man (Marzulli and Callahan, 1957). It has already been established, however, that the sweat glands of the pig are not active (see II-2.1). Therefore diffusion of water through the skin is the only endogeneous pathway by which a pig can achieve cutaneous evaporation.

Measurements made by Ingram (1964b) showed that for pigs at temperatures below the critical level, cutaneous water loss over the general body surface, but excluding the snout, was similar to that in man and other animals. At higher ambient temperatures, however, even when body temperature was elevated, water loss from pig skin was only of the order of 30 $ml/m^2/h$ and could be accounted for by the increased vapour pressure gradient consequent on the increase in skin temperature which occurred after vasodilation. The increase in total evaporative loss at a high environmental temperature detected by Mount (1962) in the new born pig could be accounted for by losses from the respiratory tract alone.

5.2 Effect of Sprinkling on the Growth Performance of Pigs

It has been shown that the pig's growth performance is increased by the use of wallows and sprinklers, both under hot-dry (Bray and Singletary, 1948; Culver, Andrews, Conrad and Noffsinger, 1960; Hale, Givens, Johnson and Southwell, 1966) and hot-humid (Hsia, Fuller and Koh, 1974) conditions. The provision of a wallow is a potential means of alleviating heat stress under extensive production systems, but under the intensive housing systems which are now common in developed countries the wallow can become an important hygiene and disease harzard, as well as representing an added capital and variable cost through cleaning. A number of alternative means of artificially wetting pigs have thus been investigated, the most common amongst which is automatic sprinkling.

The effectiveness of sprinklers in cooling and improving the performance of pigs under hot conditions depends on the duration and temperature at which they are activated. Researchers have tried different methods to wet pigs, ranging from pouring water over them to sprinkling and spraying (misting). Although pouring water over pigs is impractical under commercial situations, Bond, Heitman and Kelly (1964) have demonstrated in a short term experiment at elevated ambient temperature (35° C) that cool (22° C) water is effective in this regard.

Fine spraying (misting) may wet a pig effectively under still air conditions but under windy conditions the tiny water droplets may be carried away and be ineffective in reaching the pig (Bond, 1963). Sprinkling with water in larger droplets that are less affected by air movement than the "mists" has been investigated by a number of workers, whose results are summarized in Table 1.

In all cases (Table 1) except the report of Brennan (1978), the daily rates of gain of pigs that had been sprinkled were increased significantly. The available evidence suggests that sprinkling for 1-2 minutes every 30 to 60 minutes is sufficient to increase the daily rate of gain to non heat-stressed levels.

Table 1. Summary of the reported effects of different sprinkling regimes on the Daily Rate of Gain (DRG) of pigs.

Liveweight	Daily Rate of Gain (kg/d) Control	Duration Between Successive Sprinklings (min) 15	30	45	60	67	90	Continual	Delivery rate (ℓ/min)	Environment	Sprinkling System Operation	Sprinkling Duration	Source
28.6-98.6 60.0-93.2	0.86 0.71							0.95 0.80	1.125 1.125		24 h/d at $22^{o}C$ and above (mist)		Culver et al. (1960)
32.7-93.2		0.63	0.67					0.70	0.72		10 am - 8 pm (10 h/d)	2.5 min	Bond (1963)
27.0-93.0 24.2-93.2 22.1-94.4	0.67 0.82 0.74							0.77 0.89 0.85	1.325 1.06 1.06	$20.7-32.9^{o}C$ $18.8-30.0^{o}C$ $18.3-30.1^{o}C$	7 am - 7 pm " "		Hale et al. (1966)
26.0-98.0	0.62		0.74		0.78				2.4		14 h at $21^{o}C$ and above	1 min	Morrison et al., (1972)
26.0-98.0	0.62		0.69		0.74				2.4		6.7 h/d at $30^{o}C$ and above	1 min	
29.0-50.0 29.0-50.0 50.0-89.0 50.0-89.0	0.44 0.44 0.58 0.58			0.55 0.46 0.66 0.65		0.48 0.44 0.67 0.63	0.50 0.42 0.61 0.63		0.17	$21.0-33.0^{o}C$ $24.0-35.0^{o}C$ $21.0-33.0^{o}C$	above $25^{o}C$ above $29^{o}C$ above $21^{o}C$ above $25^{o}C$	2 min 2 min 2 min 2 min	Hsia, Fuller and Koh (1974)
25.0-90.0	0.55				0.59					$23.9-31.8^{o}C$	8 am - 5 pm 9 h/d (mist)	1 min	Ho and Khoo (1977)
32.0-79.0 27.0-93.0	0.52 0.59		0.53 0.58								12 h/d at above $25^{o}C$	2 min 2 min	Brennan (1978)

Although most workers (see Table 1) found no significant increase in feed efficiency in sprinkled pigs, one group (Hsia, Fuller and Koh, 1974) has reported such an effect.

5.3 **Drinking Water as a Cooling Agent**

It has already been established that the temperature of ingested feed may influence the growth performance of a pig and that reductions in feed intake occur when pigs are stressed by elevated ambient temperature (see II-2.3). From this it follows that cold drinking water may also act as a cooling agent and thus improve the growth performance of heat stressed individuals.

In most mammals, the intake of water is correlated with feed intake (Anand, 1961); in the pig, in particular, water intake is related to dry matter intake (Mitchell, 1962). Joshi, Singh and Bhattacharyya (1976) reported that both the feed and water consumptions (on liveweight basis) of sows were significantly lower in summer than in winter. In contrast to this however, Mount, Holmes, Close, Morrison and Start (1971) found that pigs exposed to 30° C ambient temperature consumed water at a rate of 26 ml/kg body weight or 600 ml/kg feed greater than that in similar animals maintained at 20° C.

The pigs' physiological responses to the ingestion of cooled drinking water have been measured by Bond, Heitman and Kelly (1964). At an environmental temperature of 35° C, they recorded body temperatures of 40.2, 40.1 and 39.9° C in pigs that drank water at temperatures of 35, 22 and 18° C respectively. The corresponding respiration rates were 113, 102 and 94 b/min.

Very little information is available regarding the possible beneficial effects of cold drinking water on the growth performance of pigs at high ambient temperatures. Bond (1963) reported that there was no significant difference in daily rate of gain between pigs (30 to 77 kg liveweight) on 18°C drinking water and similar pigs on 32°C drinking water when both groups were in an environment of 31°C.

6.0 PROTEIN RETENTION IN PIGS AS INFLUENCED BY HOT CLIMATES

Protein retention is a function of external (composition of feed and feed intake) and other (body weight, sex and breed) factors (Berschauer, Gaus and Menke, 1980). With respect to climate, the highest rates of protein retention have been observed in growing finishing pigs (20-100kg) in the range 15 to 23° C ambient temperature (Moustgaard, Nielsen and Sorensen, 1959), which was also the temperature range giving fastest growth and highest feed efficiency. This is due to the fact that, especially in young growing pigs, environmental temperature and plane of nutrition affect the rate of heat loss and thus the extent to which metabolizable energy (ME) from feed is converted within the body into protein and fat (Fuller and Boyne, 1972; Verstegen, Close, Start and Mount, 1973; Gray and McCracken, 1974).

Close, Mount and Brown (1978) estimated ME, heat loss and nitrogen balance in growing pigs (25-50 kg) kept at five environmental temperatures (10, 15, 20, 25 and 30° C) and on four planes of nutrition (M, 2M, 3M and 4M; where M is maintenance energy requirement at the thermoneutral ambient temperature, M=440 MJ/$kg^{0.75}$/d. Under those circumstances, protein retention was found to be influenced significantly by the level of feed intake at each environmental temperature. The increases in protein retention were 0.16, 0.15, 0.14, 0.13 and 0.12 kJ protein/$kg^{0.75}$/d/unit increase in metabolizable energy intake at 10, 15, 20, 25 and 30° C respectively. Furthermore, it was found that as a percentage of protein intake, protein retention decreased with increasing temperature (54, 46, 46, 46 and 39% at 10, 15, 20, 25 and 30° C respectively). Stombaugh and Oko (1980) simulated nutritional-environmental interactions in the pig using a computer (IBM-Continuous System Modelling Program III) and found that protein retention could be expected to increase as the concentration of protein in feed increases but to decrease as ambient temperature increases (Table 2). If it is assumed that all of the values given by Stombaugh and Oko (1980) were on a dry matter basis, then it can be calculated that protein retention as a percentage of protein intake followed a similar pattern to that of net protein retention in 20 kg pigs. However, in heavier animals protein retention as a percentage of protein intake decreased as the level of dietary protein increased from 12 to 18%.

Table 2. Predicted pig performance using computer-simulation of pigs fed a diet containing 15.9 MJ/kg *ad libitum* and standing in an environment of 55% R.H. and 1 m/s wind velocity (Adapted from Stombaugh and Oko, 1980).

Pig weight	20 kg				50 kg				80 kg			
Ambient Temperature	15°C		30°C		15°C		30°C		15°C		30°C	
Dietary protein (%)	12	18	12	18	12	18	12	18	12	18	12	18
Feed intake (g/d)	1069	1063	957	959	2041	2057	2011	2012	3178	2916	1895	1895
Net protein deposition (g/d)	48.0	78.4	41.8	68.8	89.0	130	89.0	126	126	130	64.0	65.0
Net protein deposition (% of protein intake)	37.4	41.0	36.4	39.9	36.3	35.1	36.9	34.8	33.0	24.8	28.1	19.1
Nitrogen excreted (g/d)	13.5	15.0	12.9	14.7	26.5	29.9	26.4	30.0	39.4	52.1	41.7	52.9
Total heat loss (MJ/d)	6.16	6.19	3.55	3.64	8.28	8.33	6.94	7.10	10.6	10.8	9.63	9.77

7.0 METABOLIC HEAT PRODUCTION IN PIGS

The essential feature of thermoregulation in living animals is that the rates of heat production and loss are controlled in such a way that the body core temperature remains relatively steady. Homeothermy is maintained over a wide range of environmental temperatures despite considerable variation in the temperature of the outer body shell (Mount, 1968).

A variety of means are available to measure heat loss from the body by conduction, convection, radiation and evaporation (Close, 1981). Heat production, on the other hand, may be measured indirectly by respiration calorimetry.

7.1 Calorimetry

Heat produced in the animal body as a result of the oxidation of food or tissue substrate may be measured in two ways:

a) Direct calorimetry

The principle involved in a direct calorimeter is the same as that in the common laboratory bomb calorimeter. Heat evolved increases the temperature of a surrounding medium of known specific heat and mass. In addition, there is the need to measure respiratory heat loss since some of the body heat is used to transform water to the vapour state. The first direct calorimeter for use with animals was built by Lavoisier and Laplace (see Mount, 1968) in the eighteenth century, in this case the heat released melted ice surrounding the animal. Much later, direct calorimeters to accommodate cattle or pigs were built by Armsby and Fries in America in 1903, and by Capstick and Wood at Cambridge in 1920 (see Blaxter, 1969). Although considerable automation is now possible in construction of direct calorimeters, the apparatus would still tend to be cumbersome in use and expensive to operate. Holmes (1968) described the direct calorimeter used with pigs at Cambridge. No new direct calorimeters operating on the adiabatic and flow principle have been constructed in recent years (Blaxter, 1969).

b) Indirect calorimetry

Quite distinct from the direct calorimetry approach, indirect calorimetry relies on measurement of gaseous exchange associated with metabolism. From this it is possible to compute an animal's heat production. There are two main types of indirect calorimeters:

i) Close circuit type - in which the animal is totally enclosed in a respiration chamber forming part of a sealed system. Carbon dioxide is removed from the chamber air and this is replaced by oxygen. The composition of the chamber air should remain constant as moisture is also removed. A fall in pressure in the whole apparatus occurs as a result of absorption of oxygen by the animal, and oxygen is admitted to the system in proportion to this fall in pressure. By weighing the absorbents, the amount of carbon dioxide can be measured by weight or volume (Blaxter, 1969).

ii) Open circuit type - in which the respiration chamber is opened to the surrounding air and fresh air is drawn from outside into the chamber. Open circuit calorimeters have evolved from designs originally used by Haldane and Pettenkofer (see Kleiber, 1961). The use of the diaferometer and other devices for measuring concentration of oxygen and carbon dioxide is now making the open circuit method both easier to use and more accurate. This type of calorimeter was employed in the study of the effect of high ambient temperature on metabolic heat production of pigs presented in this thesis (see III-9.0).

7.2 **Metabolic Heat Production and Heat Stress in Pigs**

In all living animals, metabolic body heat as a result of the oxidation of food and a range of normal physiological activities may contribute to the stress experienced by individuals exposed to high environmental temperatures. In the case of pigs, metabolic heat production is now known to be influenced by various factors.

Estimates of the heat production of pigs of different liveweights when fed different amounts of dietary energy (Table 3) were summarized by Holmes and Close (1977) from a number of published papers (Jenkinson, Young and Ashton, 1967; Jordan and Brown, 1970; Kielanowski and Kotarbinska, 1970; Fuller and Boyne, 1972; Burlacu, Baia, Ionila, Moisa, Tascenco, Visan and Stoica, 1973; Holmes, 1973, 1974; Holmes and Breirem, 1973; Verstegen *et al.*, 1973; Jordan, 1974; Thorbek, 1974, 1975). These data indicate that under thermoneutral conditions the metabolic heat production is higher in younger and lighter pigs than in older and heavier ones.

Table 3. Heat production of pigs of different ages and liveweights when fed different amounts of energy under thermoneutral conditions (adapted from Holmes and Close, 1977)

	Metabolisable energy intake			
	0	M	2M	3M
	Heat production (MJ/kg $W^{0.75}$ daily)			
Milk-fed				
Newborn	0.531	0.573	0.640	0.707
Young	0.406	0.494	0.565	0.636
Solid-fed				
Young	-	0.649	0.795	0.941
20-50 kg	0.397	0.423	0.561	0.699
50-100 kg	0.364	0.410	0.527	0.644

M = metabolised energy required for maintenance; assumed to be 0.42 MJ ME per kg$W^{0.75}$ daily.

Furthermore, heat production is clearly influenced by the energy intake of the pigs. As can be seen in Table 3, the higher the metabolizable energy intake the higher the heat production. The lowest values were recorded in fasting pigs, while there was about a 42% increase in metabolic heat production as energy intake rose to three times the maintenance level.

Heat production is also influenced by ambient temperature. Evidence from several workers (Table 4) indicates that metabolic heat production increases as ambient temperature falls below the thermoneutral zone. At temperatures above the thermoneutral zone, metabolic heat production also declines at first before rising again at very high ambient temperatures.

Other external factors such as ambient humidity, wind velocity and solar radiation may also influence metabolic heat production in pigs. Ingram (1965b) found that humidity had no clear effect on metabolic heat production in the pig. However, since an increase in humidity from 33 to 80% at 35° C ambient temperature caused a threefold increase in respiration rate and a steady rise in deep body temperature in pigs (20-25 kg; Ingram, 1965b), the extra work of breathing at higher frequencies (Otis, 1954) and faster chemical reaction due to the van't Hoff effect may cause an increase in metabolic heat production.

Increasing wind velocity may also increase metabolic heat production in pigs. Mount (1966) found that the heat production of individual new born pigs was increased by 12 to 16% by a wind velocity of 0.35 to 0.82 m/s over the body and by 19 to 38% by a wind velocity of 1.58 m/s at ambient temperatures of 20 and 30° C. Close, Heavens and Brown (1981) reported an increase of heat production in older individual pigs (20-23 kg) of 20, 31 and 17% at ambient temperatures of 10, 20 and 30° C, respectively.

There is little information in relation to influence of radiation on metabolic heat production in growing-finishing pigs. However, in new born pigs where one way of supplementary heating is by using infra-red lamps, Mount (1964) found that in two kilogram pigs the radiant heat loss was 50% of total non-evaporative heat loss at 20° C ambient temperature. At an ambient temperature of 30° C, radiation heat loss was 58% of total non-evaporative heat loss. Stephens and Start (1970) reported that the application of radiant heat to piglets resulted in an 18% reduction in heat production at ambient temperature of 10 to 20° C.

Table 4. Metabolic heat production of pigs living at various environmental temperatures.

Live-weight (kg)	Environ-mental temperature (°C)	Metabolic heat (kJ/kg $W^{.75}$ /d)	Feeding	Calori-meter used	Source
23-42	20	651	39g/kg Lwt	Direct	Close,
23-42	20	699	45g/kg Lwt	Direct	Verstegen
23-42	8	783	45g/kg Lwt	Direct	and Mount
23-42	8	792	52g/kg Lwt	Direct	(1974)
37-64	25	548	+feed	Indirect	Holmes
37-64	33-35	573	+feed	- Open	(1973)
				circuit	
25-75	25	564	+feed	Indirect	Holmes
25-75	33-35	581	+feed	- Open	(1974)
25-75	25	397	fast	circuit	
25-75	33-35	380	fast		
25-30	18	542	fast	Indirect	Thorbek
25-30	26	452	fast	- Open	(1974)
55-80	18	442	fast	circuit	
55-80	26	299	fast		
95-110	16	548	fast		
95-110	22	434	fast		
95-110	26	328	fast		
25-39	20	602	39g/kg Lwt	Direct	Close
25-39	20	448	fast	Direct	and
29-34	20	660	45g/kg Lwt	Direct	Mount
29-34	20	467	fast	Direct	(1975)
28-38	30	662	39g/kg Lwt	Direct	
28-38	30	362	fast	Direct	
30-36	30	737	45g/kg Lwt	Direct	
30-36	30	399	fast	Direct	
Initial	20	575	+feed	Indirect	Dividich,
5-8kg	24	532	+feed	- Open	Vermoral,
over 14-15d	28	481	+feed	circuit	Noblet,
					Bouvier
					and
					Aumaitre
					(1980)

8.0 CONCLUSION

The preceeding review demonstrates that little information is currently available on the likely effects of high temperatures on pig growth under commercial situations in Australia. In addition, conflicting reports exist in the overseas literature on the likely benefits to pigs under heat stress conditions of variation in such factors as dietary energy and protein and the level and type of dietary fat. While sprinkling and the provision of cooled drinking water have been shown to be beneficial, little is known of detailed application, particularly in Australia where water supplies are often limited. There is no information available on metabolic heat production in growing-finishing pigs related to growth performance in a high ambient temperature. The experimental sections which follow aim to remedy these deficiencies while at the same time extending our understanding of the mechanisms by which pigs adapt to hot climates.

III. EXPERIMENTAL

1.0 INTRODUCTION

With the overall aim of improving pig production in tropical and subtropical conditions in Australia, the present study was designed specifically to investigate:

a) Performance of commercial pigs in different climatic zones in Australia - data from a Field Survey (III-2.0).

b) The performance of commercial pigs as affected by ambient temperature and season of year (III-3.0; Field Experiments 1, 2 and 3).

c) Effects of level of dietary energy and protein on the performance of pigs raised in hot environments (III-4.0; Laboratory Experiment 1 and 2).

d) Effects of level and type of dietary lipid on the performance of pigs raised under high ambient temperatures (III-5.0; Laboratory Experiments 3 and 4).

e) Temperature and dietary influences on nitrogen retention (III-6.0; Laboratory Experiment 5).

f) Amelioration of heat stress by utilization of water (III-7.0 and 8.0; Laboratory Experiments 6 and 7).

g) Metabolic heat production of pigs exposed to hot climates (III-8.0; Laboratory Experiment 8).

All computations in the studies were done on a mainframe computer DECSYSTEM-2060 (Digital Equipment Corporation, Marlboro, Massachusetts, U.S.A.) using the following statistical packages and programs:-

a) Minitab (University of Pennsylvania, U.S.A.) for general computation.

b) NEVA (Burr, 1976) and BMDP (University of California, U.S.A.) for analysis of variance.

c) BAR3 (Burr, 1975) for multiple regression analysis.

d) SPSS (University of California, U.S.A.) for canonical correlation analysis which was used for estimation of the linear function of two sets of variables which were most closely associated (Bofinger and Wheeler, 1975).

e) <Plot79> package (University of Utah, U.S.A.) for plotting graphs.

2.0 FIELD SURVEY - THE PERFORMANCE OF COMMERCIAL PIGS IN DIFFERENT CLIMATIC ZONES IN AUSTRALIA

2.1 Introduction

Pig production in Australia dates from the early days of British colonization. With the growth of the dairy industry early in the 19th century came the development of a commercial pig industry based on skim milk. Since the 1930's, however, there has been an upsurge in pig numbers on grain growing properties. At this time it is estimated that there are about 2.35 million pigs in Australia (Anon, 1982); these pigs are raised under various conditions ranging from extensive to intensive minimal disease units. Commercial piggeries are situated in various parts of the country, they range from tropical to temperate in climatic conditions.

2.2 Materials and Methods

To determine the effects of environment on the growth performance of pigs, it is necessary to firstly classify the various climatic zones, and secondly to gather data for analysis from piggeries situated in the different climatic zones.

Twenty six commercial producers were approached to provide pig performance and climatic data on a month by month basis. The producers concerned varied in location from Kingaroy in Queensland (26° S) to Tasmania (42° S), and in climate from humid coastal (e.g. Brisbane, Queensland) to dry inland (e.g. Grong Grong, N.S.W.).

In the present study the zones were defined objectively using the method of Bonsma, Van Marle and Hofmeyer (1953) whereby mean air temperature is plotted against mean relative humidity (R.H.) on a monthly basis to form a climograph (Figure 1). Each producer was asked to provide the following data for each month of the year:-

a) The sex and type of pigs produced (i.e. porker or baconer).

b) Daily rate of gain (DRG).

c) Feed conversion ratio (FCR).

d) Backfat depth (P2), see Figure 20, page 100.

e) Meteorological data, preferably from within the same grower shed.

The linear, quadratic and cubic coefficients in the polynomial regressions were tested for homogeneity, initially within the pooled data for DRG, FCR and P2. As significant heterogeneity was observed, further tests for homogeneity were considered necessary. In the first instance data within zones were pooled and between-zone statistical tests were conducted. This was followed by between-farm tests within each of the zones. With respect to the subsequent statistical analyses of the relationships between climate and pig performance, data for each of the biological parameters were pooled whenever homogeneity was established. In the absence of homogeneity, separate analyses were conducted for each farm.

The parameters were regressed against month and maximum, minimum and mean temperatures using multiple regression analysis (Steel and Torrie, 1980), where,

$$\text{Mean temperature} = \frac{(\text{Max.temp.} + \text{Min.temp.})}{2}$$

Multivariate correlation analysis using the canonical technique was also applied to the parameters in order to establish the relative importance of the independent variables (i.e. meteorological data). Since the mean temperature was derived from maximum and minimum temperatures, the canonical analyses were applied to the parameters with month, maximum and minimum temperatures only.

2.3 Results

Twenty five of the 26 potential sources of data approached responded and supplied some of the data requested, although only 14 of these provided records for more than seven consecutive calendar months (the minimum considered necessary for adequate analysis). Out of these 14 only 2 supplied shed temperatures and it was thus necessary to discard this information and substitute meteorological data from the recording station (Climate data, Division of Land Use and Research, CSIRO) closest to each of the piggeries. The locations of the 14 piggeries and their closest meteorological stations are given in Table 5.

In addition, data on monthly variation in backfat depth in the State of Tasmania was made available by Mr. A. C. Hughson of the Department of Agriculture. This information was in the form of abattoir killing sheets and related to pigs supplied by six commercial producers, each of whom had pigs slaughtered in at least seven of the 12 months studied. As information on only 720 individual pigs was available, the data were pooled, as were those from the meteorological stations nearest to each farm (Table 5).

Table 5. Location of data sources and their closest meteorological stations.

	Data source	Meteorological station
1	Kingaroy, Queensland	Kingaroy, Queensland
2	Toowoomba, Queensland	Toowoomba, Queensland
3	Warwick, Queensland	Warwick, Queensland
4	Gatton, Queensland	Gatton, Queensland
5	Brisbane, Queensland	Brisbane, Queensland
6	Murwillumbah 1, N.S.W.	Lismore, N.S.W.
7	Murwillumbah 2, N.S.W.	Lismore, N.S.W.
8	Pine Ridge, N.S.W.	Gunnedah, N.S.W.
9	Temora, N.S.W.	Temora, N.S.W.
10	Grong Grong, N.S.W.	Wagga Wagga, N.S.W.
11	Corowa 1, N.S.W.	Albury, N.S.W.
12	Corowa 2, N.S.W.	Albury, N.S.W.
13	Corowa 3, N.S.W.	Albury, N.S.W.
14	Bendigo, Victoria	Bendigo, Victoria
15	Various piggeries, Tasmania	Hobart + Launceston + Swansea + Scotdale, pooled, Tasmania

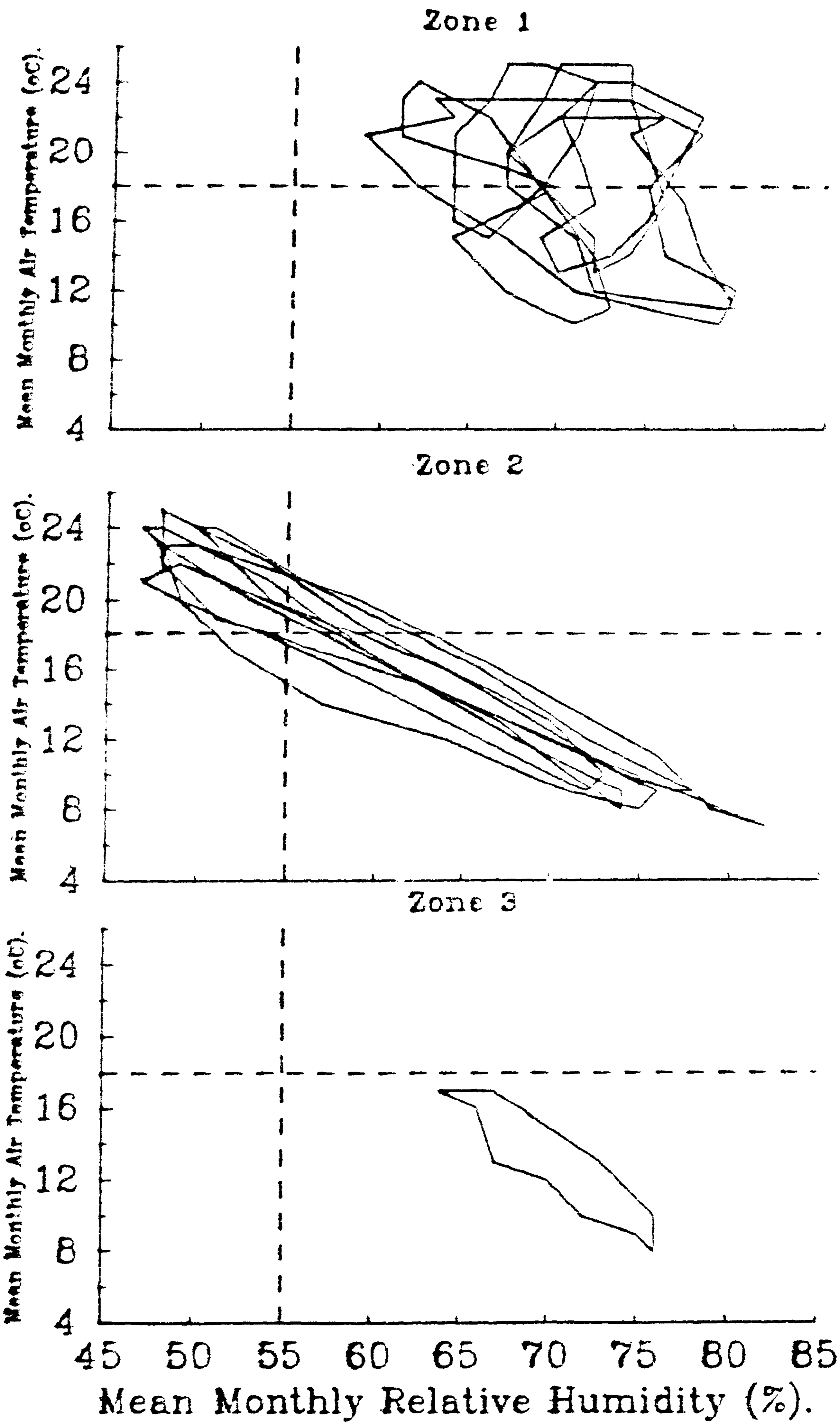

Figure 1. Climographs of the 3 zones illustrated in Figure 2. The separate frames shown for zones 1 and 2 are those from each of the individual meteorological stations concerned.

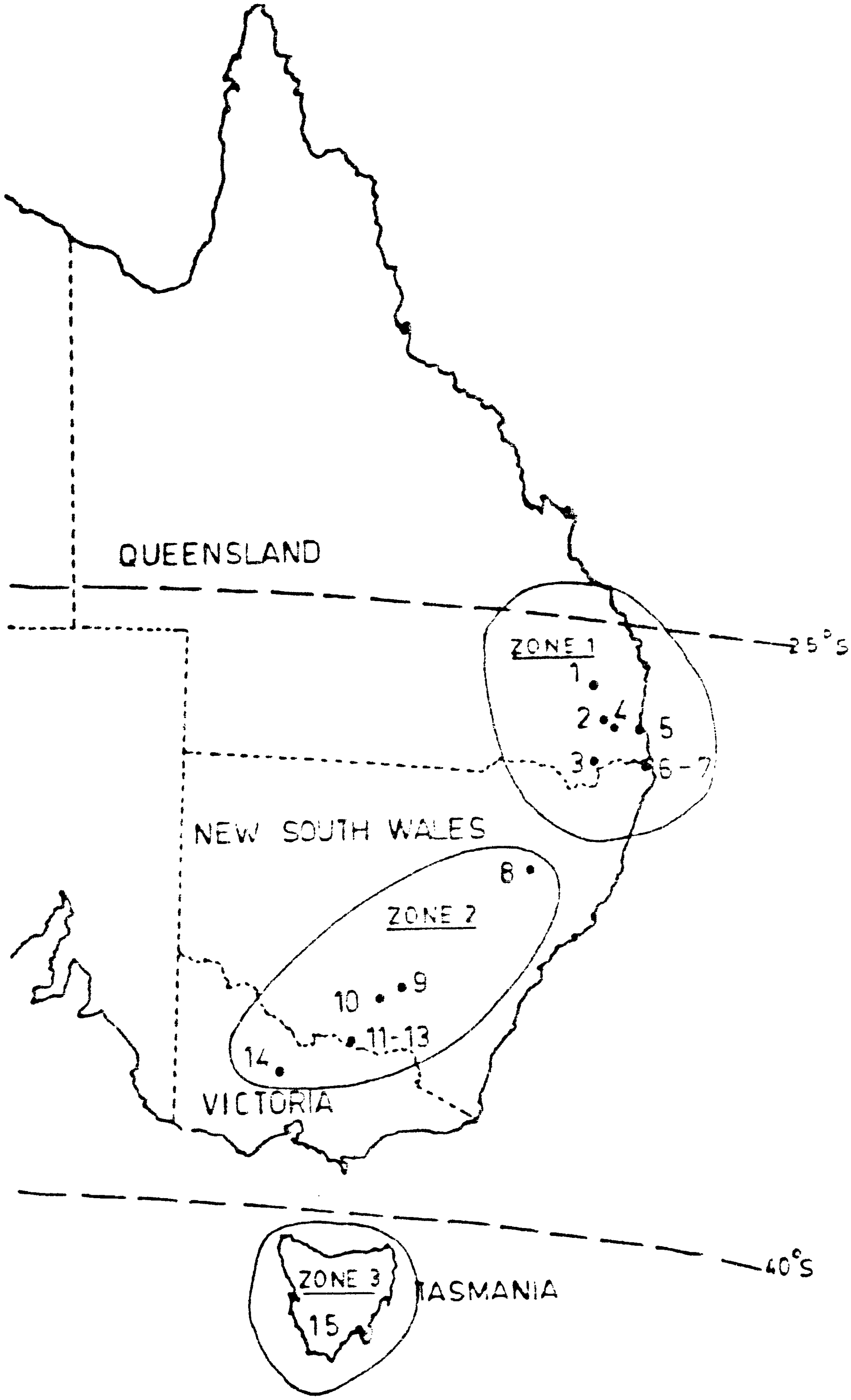

Figure 2. Map showing the geographical locations of the 15 sources (see Table 5) that contributed seasonal production data and the boundaries of the climatic zones into which they are divided.

The climographs in Figure 1 reveal that the meteorological stations closest to the data sources can be classified into 3 distinct zones as follows:-

a) Zone 1, consisting of Kingaroy, Toowoomba, Warwick Brisbane in Queensland and Murwillumbah (2) in N.S.W.

b) Zone 2, consisting of Pine Ridge, Temora, Grong Grong, Corowa (3) in N.S.W., and Bendigo in Victoria.

c) Zone 3, consisting of the state of Tasmania.

The geographical location of these towns and the boundaries of the climatic zones derived are illustrated in Figure 2.

2.3.1 Homogeneity Test

Since data from Brisbane were for porkers only and the piggery at Temora was fitted with sprinklers which would be expected to modify responses to high temperature, these two sources were excluded from the homogeneity tests, the results of which (Table 6) revealed significant heterogeneity between producers in the pooled data. However, homogeneity was achieved when zones were treated as sources and data within zones were pooled. The results which follow are thus presented on an overall, zone or farm basis depending on the level of homogeneity recorded for each parameter.

2.3.2 Daily Rate of Gain (DRG)

The pooled DRG for zones 1+2 when regressed against month of the year (Figure 3) revealed a suggestion of a significant ($P<0.10$) quadratic trend (linear, $P<0.05$) such that maximum DRG occurred in July (594 g/d), the month

Table 6. Results of homogeneity tests conducted on the data collected from 14 commercial piggeries in the field survey.

Biological Parameter	Month of Year			Meteorological Parameter								
				Maximum Temp.			Minimum Temp.			Mean Temp.		
	Lin.	Qua.	Cub.	Lin.	Qua.	Cub.	Lin.	Qua.	Cub.	Lin.	Qua.	Cub.
DRG:												
All farms pooled	***	N.S.	N.S.	N.S.	N.S.	***	*	N.S.	N.S.	N.S.	N.S.	N.S.
Zone 1	**	N.S.	N.S.	N.S.	N.S.	N.A.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
Zone 2	**	*	*	N.S.	N.S.	N.S.	*	N.S.	N.S.	*	N.S.	N.S.
All zones pooled	N.S.	N.S.	N.S.	N.S.	N.S.	**	N.S.	N.S.	*	N.S.	N.S.	*
FCR:												
All farms pooled	***	***	**	*	N.S.	N.A.	*	N.S.	N.S.	*	N.S.	N.S.
Zone 1 only	N.S.	***	N.S.	N.S.	N.S.	N.A.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
All zones pooled	***	*	***	***	N.S.	N.A.	*	N.S.	N.S.	**	N.S.	N.S.
FE:												
All farms pooled	***	N.S.	***	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
Zone 1 only	N.S.	N.S.	***	N.S.	N.S.	N.A.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
All zones pooled	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

Significant results indicated by the asterisk notation imply heterogeneity. Such data were not subjected to further analysis in the pooled form.

with the lowest maximum temperature. The lowest DRGs occured in January and December (545 and 571 g/d) when maximum temperatures were high.

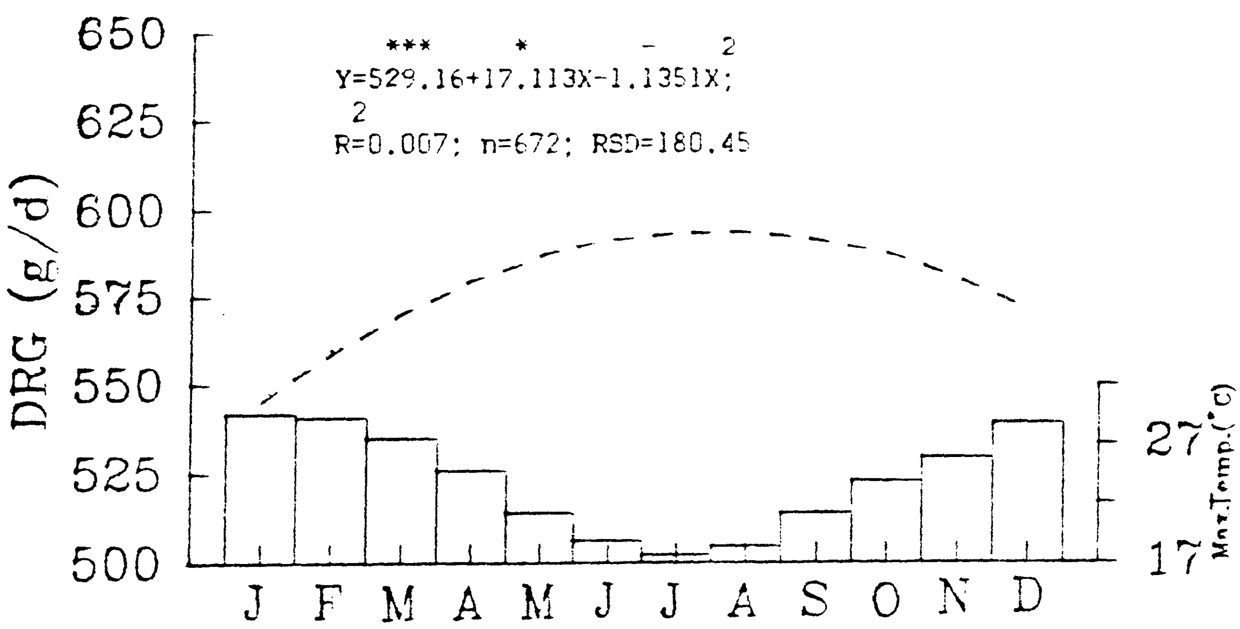

Figure 3. Daily Rate of Gain (DRG) of pigs in zones 1+2 over a 12 month period.

When DRG was regressed against the various temperature parameters, it was found to decline (P<0.001) at the rate of 10.4 (Figure 4) and 10.0 (Figure 5) g/d/°C with increments in maximum and mean temperature respectively. There were no significant linear, quadratic or cubic relationships between DRG and minimum temperature.

The DRG data were then separated into climatic zones 1 and 2. The results of regression analyses revealed that there were no significant relationships between DRG and month of the year for the pigs raised in zone 1. DRG did, however, decline (P<0.001) at rates of 12.4 , 11.3 and 9.7 g/d/°C rise in maximum (range 16 to 32°C), mean (Figure 6) and minimum

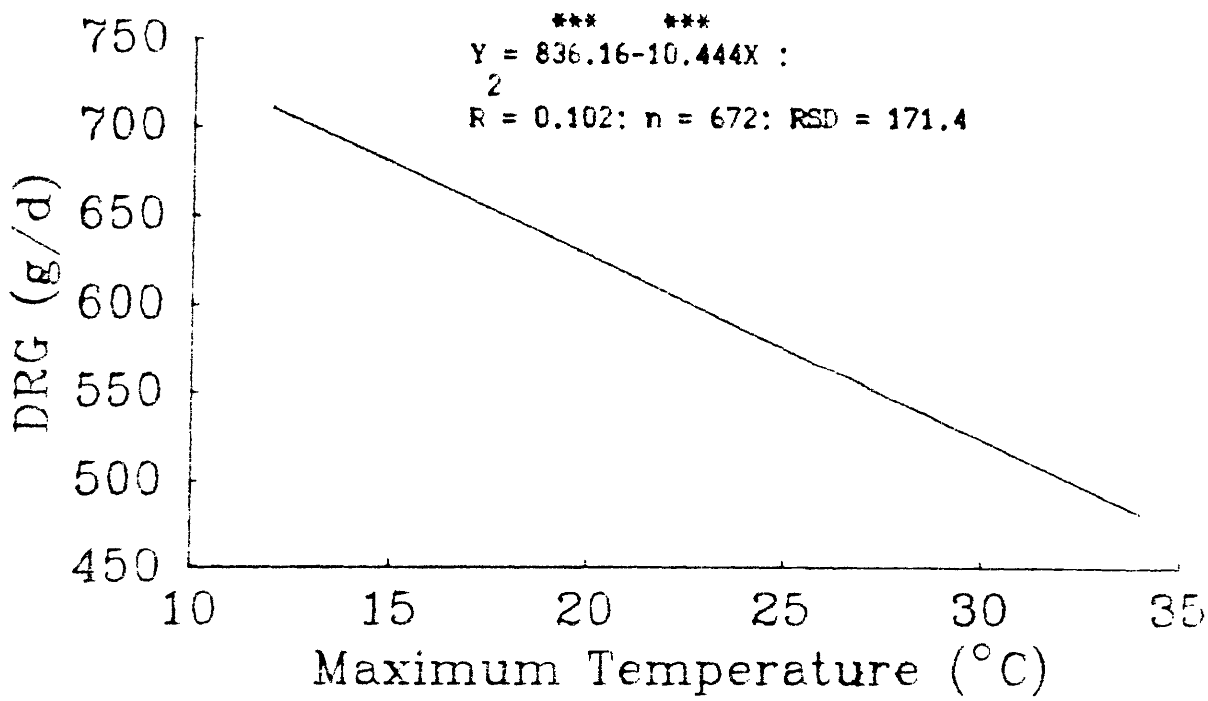

Figure 4. Daily Rate of Gain (DRG) of pigs in zones 1+2 as related to the mean monthly maximum temperature.

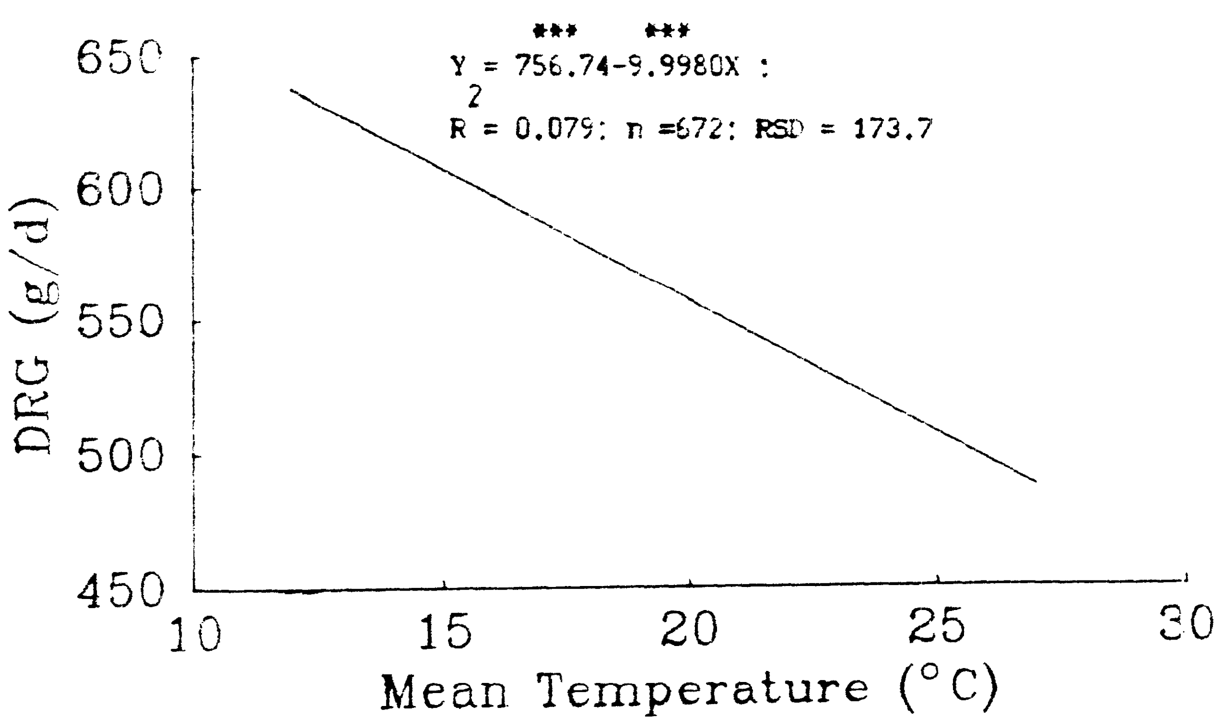

Figure 5. Daily Rate of Gain (DRG) of pigs in zones 1+2 as related to the mean monthly temperature.

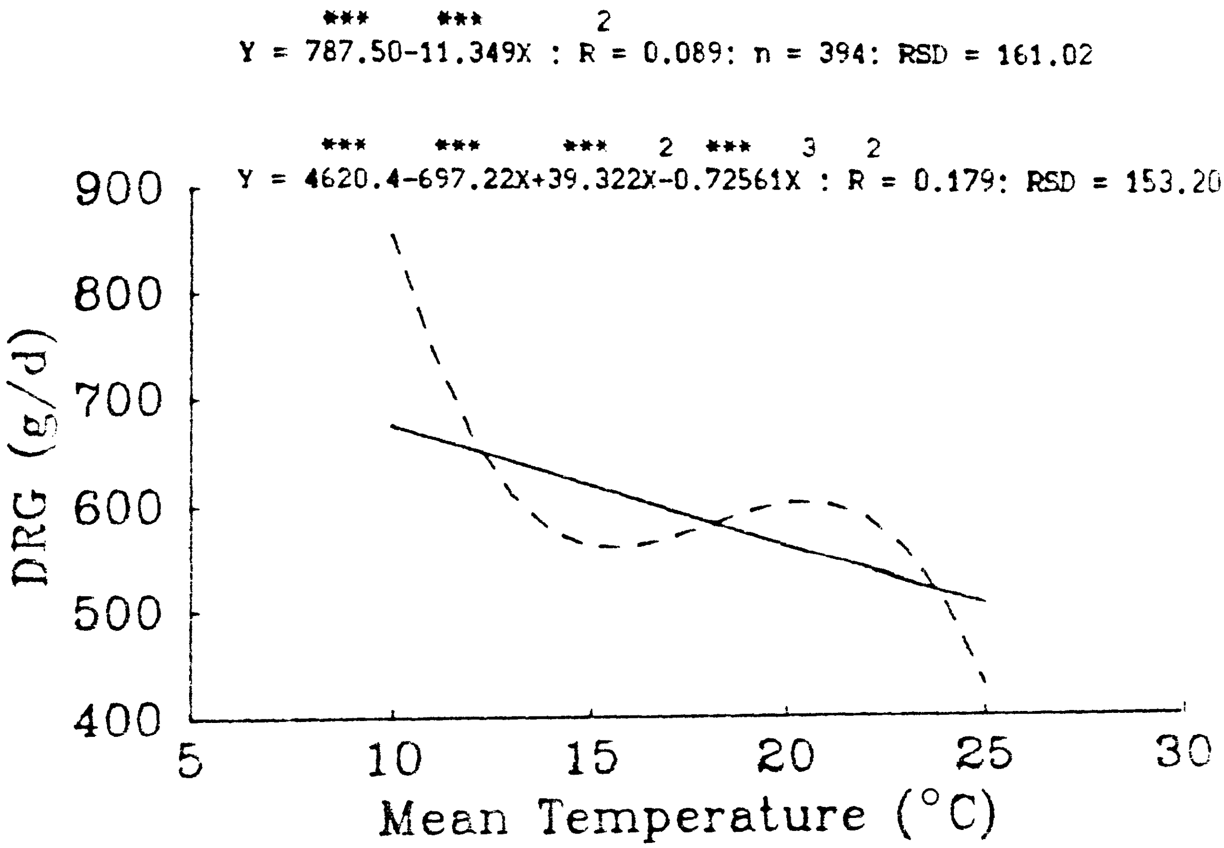

Figure 6. Daily Rate of Gain (DRG) of pigs raised in zone 1 as related to the mean monthly temperature.

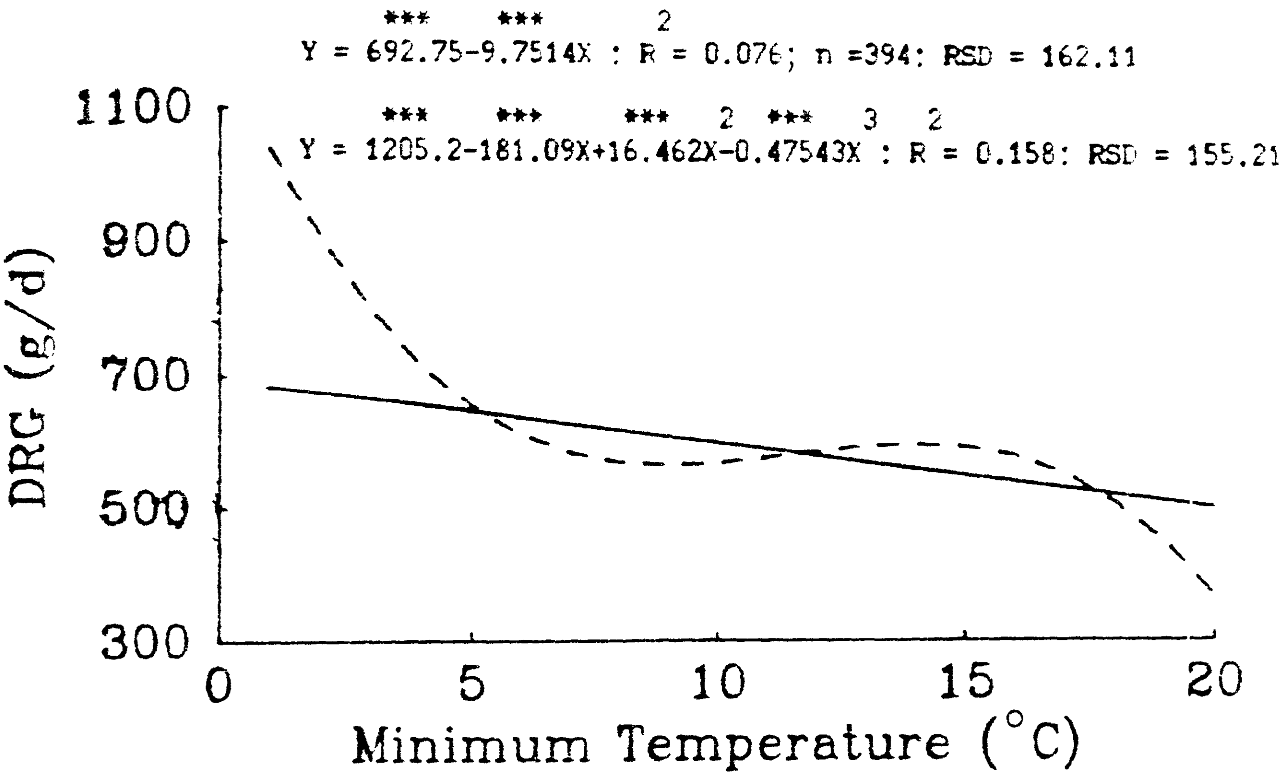

Figure 7. Daily Rate of Gain (DRG) of pigs raised in zone 1 as related to the mean monthly minimum temperature.

(Figure 7) temperatures. Curvilinear (cubic) relationships were detected between DRG and both mean (Figure 6; $P<0.001$) and minimum (Figure 7; $P<0.001$) temperatures, and these indicate that when mean or minimum temperatures were higher than 20 or 14° C DRG declined at the rates of 45.5 and 36.3 g/d/° C respectively.

Within zone 2, DRG was significantly related to maximum ($P<0.001$), mean ($P<0.001$) and minimum ($P<0.001$) temperatures. The results of the linear regression analyses revealed that DRG declined at the rate of 9.5 g/d/° C rise of maximum temperature (Figure 8). The cubic relationships between DRG and both maximum and mean temperatures (Figures 8 and 9) indicate that when these parameters exceeded 27 and 19° C respectively, growth rates declined at 29.3 and 43.5 g/d/° C, respectively.

The quadratic relationship ($P<0.001$) between DRG and minimum temperature (Figure 10) indicated that the optimum minimum temperature for growth was about 9° C.

Since heterogeneity amongst farms was detected (Table 6) DRG from each farm were also analysed separately. A summary of these results is presented in Table 7 while the results of the corresponding regression and canonical analyses are given in Appendices II and IV respectively.

From Table 7 it can be seen that the general trend was for DRG to decline with progressive increments in maximum, minimum and mean temperatures. The DRG also tended to vary over the year; increasing when air temperature was decreasing (autumn) and decreasing as air temperature increased in spring. The maximum and minimum growth rates coincided with the winter and summer seasons, respectively. A typical result is illustrated in Figure 3.

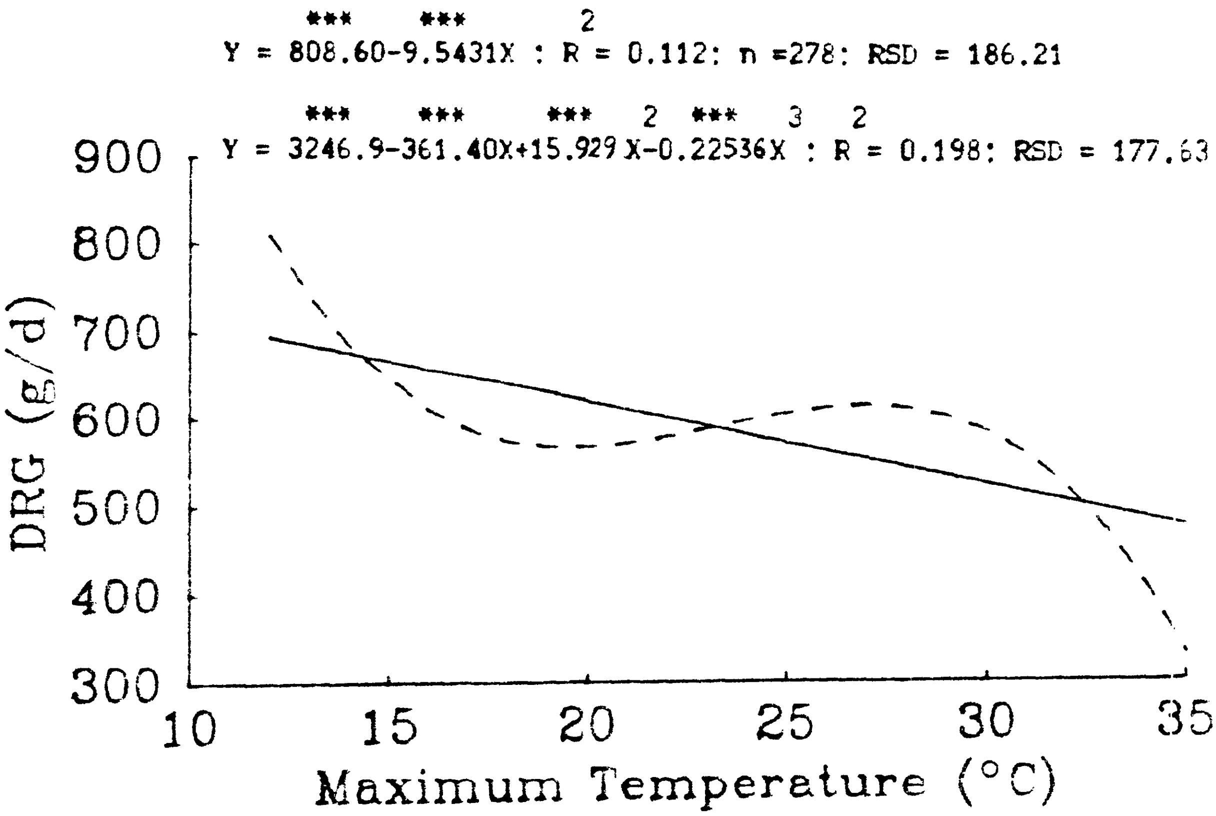

Figure 8. Daily Rate of Gain (DRG) of pigs raised in zone 2 as related to the mean monthly maximum temperature.

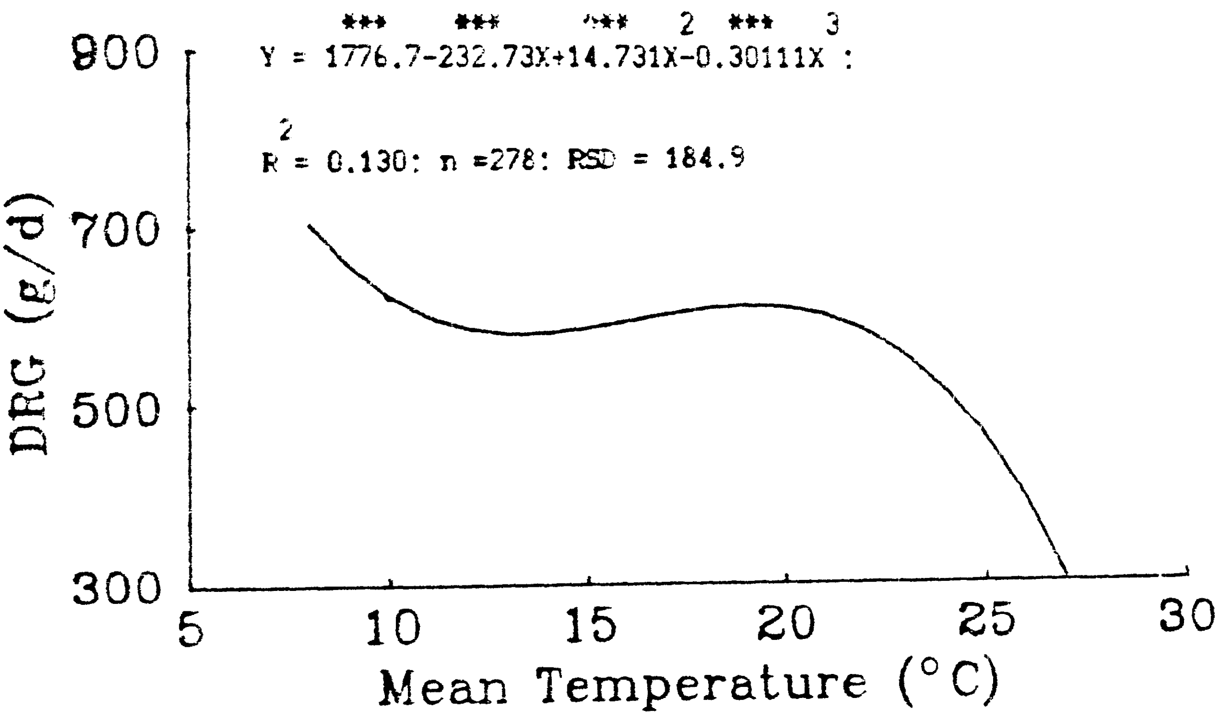

Figure 9. Daily Rate of Gain (DRG) of pigs raised in zone 2 as related to the mean monthly temperature.

Table 7. Overall trends in the relationships between month of year and monthly maximum, minimum and mean air temperatures and the Daily Rate of Gain (DRG) of pigs raised under commercial conditions in different climatic zones in Australia.

	Air Temperature (°C)			
	Month	Maximum	Minimum	Mean
		Zone 1		
Kingaroy	N.S.	N.S.	N.S.	N.S.
Toowoomba	N.S.	C	C	C
Warwick	↑	↓	↓	↓
Gatton	C	N.S.	N.S.	N.S.
Brisbane	C	N.S.	N.S.	C
Murwillumbah 1	C	↓	↓	↓
Murwillumbah 2	↓	↑	N.S.	↑
		Zone 2		
Pine Ridge	C	↓	↓	↓
Temora	C	↑	N.S.	↑
Grong Grong	↓	C	N.S.	C
Corowa 1	N.S.	N.S.	N.S.	N.S.
Corowa 2	N.S.	N.S.	N.S.	N.S.
Corowa 3	N.S.	N.S.	N.S.	N.S.
Bendigo	C	↓	↓	↓
		Zone 3		
Tasmania	N.A.	N.A.	N.A.	N.A.

↑ A significant linear increase with respect to increments in air temperature.
↓ A significant linear decrease with respect to increments in air temperature.
C Statistically significant quadratic or cubic relationships.
N.S. No significant trends.
N.A. Data not available.

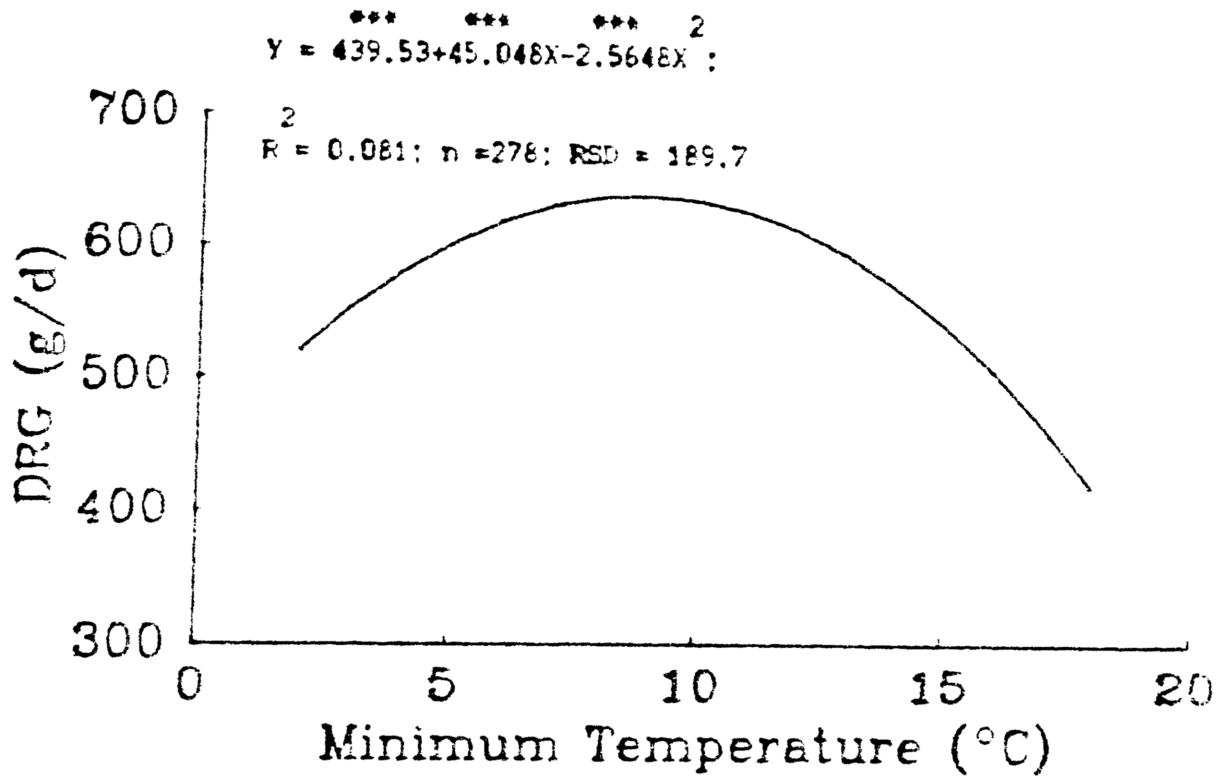

Figure 10. Daily Rate of Gain (DRG) of pigs raised in zone 2 as related to the mean monthly minimum temperature.

The canonical analyses (Appendices III and IV) indicated that time of year was relatively less important than both maximum and minimum temperature in its influence on DRG. Furthermore, maximum temperature was found to be relatively more important than minimum temperature in all zones, within each zone, and at the farm level except in the case of the farms at Brisbane and Temora.

2.3.3 Feed Conversion Ratio (FCR)

The only significant relationships observed in the pooled data were quadratic ones between FCR and maximum ($P<0.05$) and mean ($P<0.05$) monthly temperatures (Figures 11 and 12 respectively). These results suggest that the pigs converted most efficiently at a maximum temperature of 22°C and a mean temperature of 16°C.

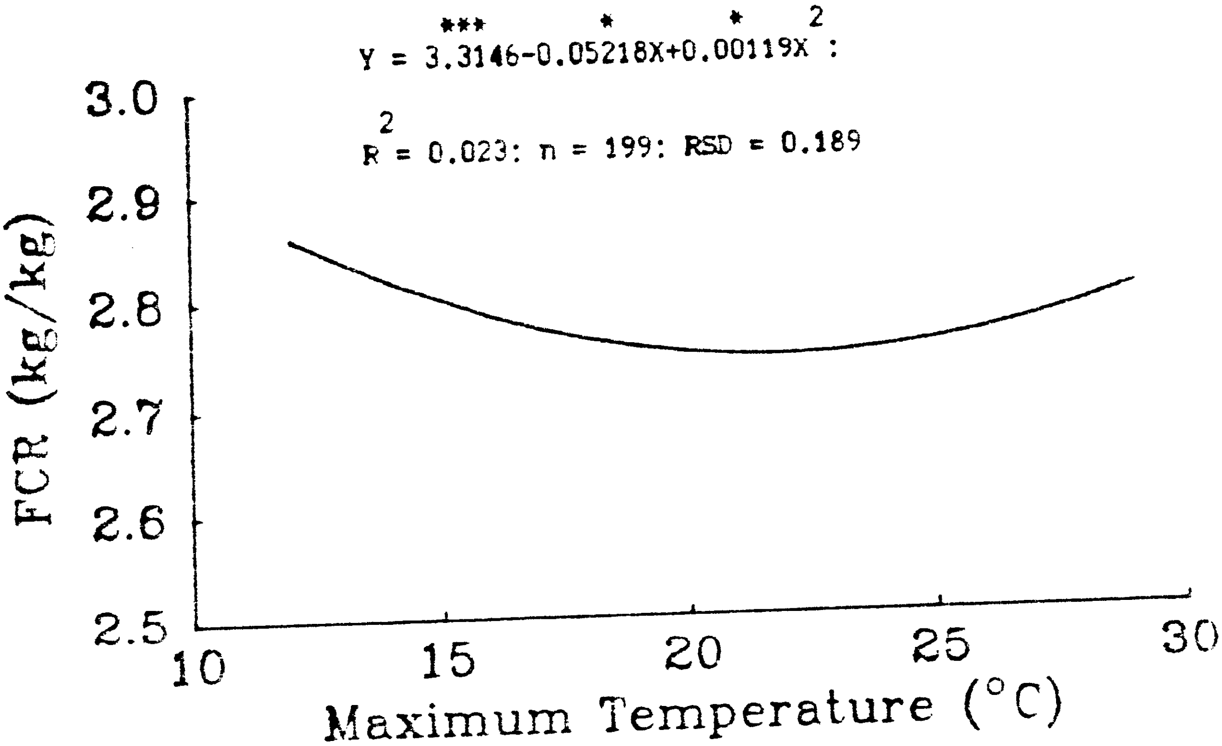

Figure 11. Feed Conversion Ratio (FCR) of pigs in zones 1+2 as related to the mean monthly maximum temperature.

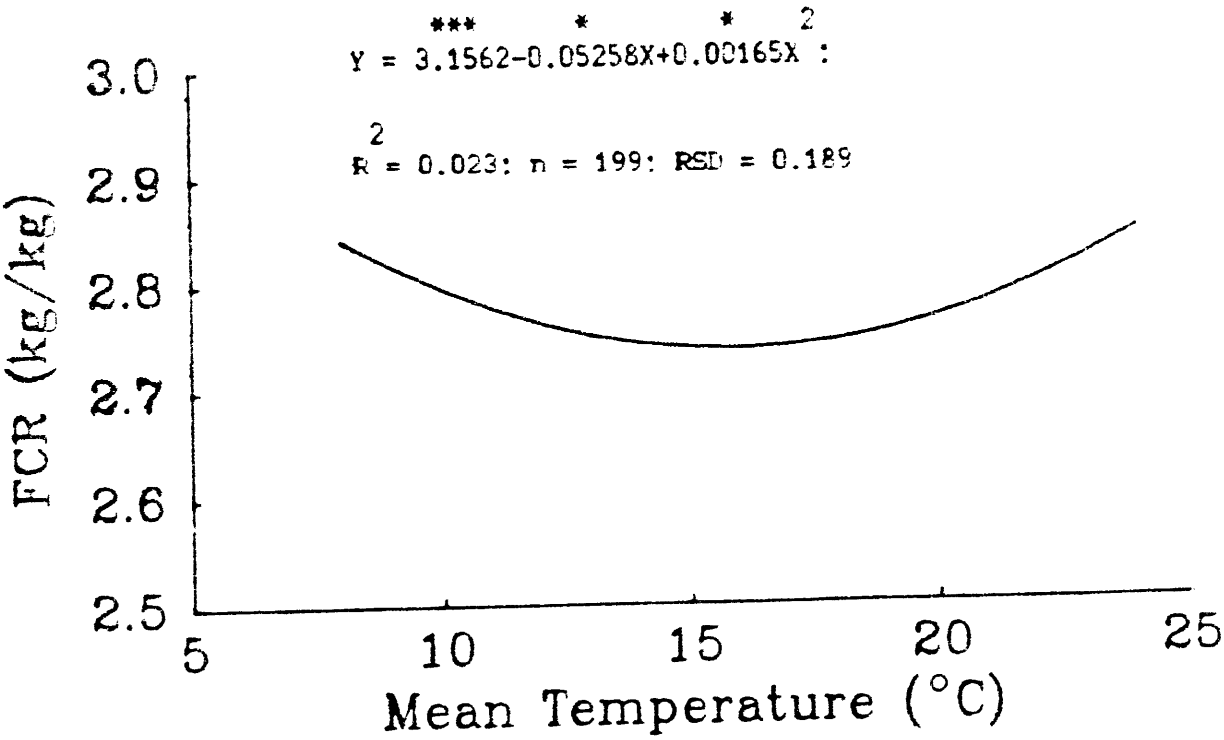

Figure 12. Feed Conversion Ratio (FCR) of pigs in zones 1+2 as related to the mean monthly temperature.

Table 8. Overall trends in the relationships between month of year and monthly maximum, minimum and mean air temperatures and Feed Conversion Ratio (FCR) in pigs raised under commercial conditions in different climatic zones in Australia.

	Month	Air Temperature (°C)		
		Maximum	Minimum	Mean
Zone 1				
Kingaroy	C	↑	↑	↑
Toowoomba	N.A.	N.A.	N.A.	N.A.
Warwick	↓	N.S.	N.S.	N.S.
Gatton	N.A.	N.A.	N.A.	N.A.
Brisbane	N.A.	N.A.	N.A.	N.A.
Murwillumbah 1	N.A.	N.A.	N.A.	N.A.
Murwillumbah 2	N.A.	N.A.	N.A.	N.A.
Zone 2				
Pine Ridge	N.A.	N.A.	N.A.	N.A.
Temora	N.A.	N.A.	N.A.	N.A.
Grong Grong	N.A.	N.A.	N.A.	N.A.
Corowa 1	N.A.	N.A.	N.A.	N.A.
Corowa 2	N.A.	N.A.	N.A.	N.A.
Corowa 3	N.A.	N.A.	N.A.	N.A.
Bendigo	C	N.S.	↓	↓
Zone 3				
Tasmania	N.A.	N.A.	N.A.	N.A.

↑ A significant linear increase with respect to increments in air temperature.
↓ A significant linear decrease with respect to increments in air temperature.
C Statistically significant quadratic or cubic relationships.
N.S. No significant trends.
N.A. Data not available.

Within zone 1, significant linear relationships were observed between FCR and maximum ($P<0.01$), mean ($P<0.01$) and minimum ($P<0.01$) temperatures. The relationships were such that FCR increased at the rate of 0.011, 0.012 and 0.009 kg/kg/°C increment in maximum, mean and minimum temperature respectively.

Since the homogeneity tests (Table 6) revealed significant heterogeneity between farms within zone 1, FCR data from each farm were analysed seperately. A summary of these results is presented in Table 8, while the results of the respective regression and canonical analyses are given in Appendices II and IV. From Table 8 it can be seen that only three piggeries provided data on FCR; two of these were in zone 1 and the other in zone 2. The results from these piggeries are contradictory: while FCR at Kingaroy (zone 1) increased with maximum ($P<0.01$), minimum ($P<0.01$) and mean ($P<0.01$) air temperature, no such significant trends were apparent amongst pigs at Warwick. In the farm at Bendigo in zone 2, only increasing minimum ($P<0.05$) and mean ($P<0.05$) temperatures were significantly related to FCR (in both cases negatively).

2.3.4 **Backfat Depth (P2)**

The significant linear relationships obtained (Figures 13 and 14) when P2 (zones 1+2+3) was regressed against maximum ($P<0.01$) and mean ($P<0.05$) temperatures indicated that backfat depth declined at the rates of 0.067 or 0.059 mm/°C rise in maximum and mean temperature respectively. The cubic relationships recorded between these independent variables and P2 revealed that backfat depth increased slightly as maximum ($P<0.05$) and mean ($P<0.05$) temperatures increased from 20 to 25, and 14 to 20°C respectively. When the maximum and mean temperatures were higher then 25 and 20°C respectively, P2 declined at an accelerating rate.

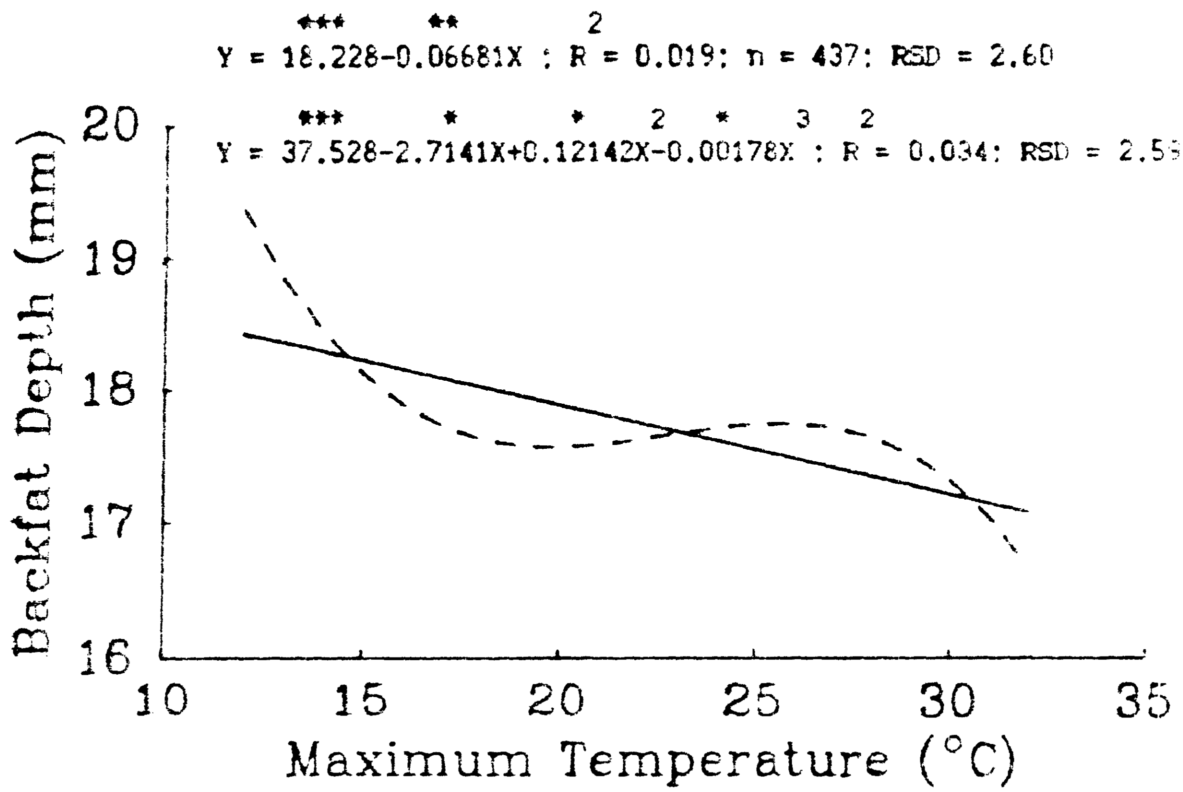

Figure 13. Backfat Depth (P2) of pigs in zones 1+2+3 as related to the mean monthly maximum temperature.

Since the homogeneity tests (Table 6) revealed significant heterogeneity between farms, backfat depth data from each farm were analysed separately. A summary of these results is presented in Table 9 and the results of the regression and canonical analyses are given in Appendices II and IV respectively. The effect of air temperature on P2 varied, especially in zone 1. From Table 9 it can be seen that in most cases there were no significant relationships between air temperatures and P2. Nevertheless on one farm in zone 1 it was found that the P2 increased

Table 9. Overall trends in the relationships between month of year and monthly maximum, minimum and mean air temperatures and Backfat Depth (P2) of pigs raised under commercial conditions in different climatic zones in Australia.

		Air Temperature (°C)		
	Month	Maximum	Minimum	Mean
		Zone 1		
Kingaroy	C	N.S.	C	N.S.
Toowoomba	↓	N.S.	N.S.	N.S.
Warwick	C	N.S.	N.S.	N.S.
Gatton	C	↑	↑	↑
Brisbane	C	N.S.	N.S.	N.S.
Murwillumbah 1	N.A.	N.A.	N.A.	N.A.
Murwillumbah 2	N.A.	N.A.	N.A.	N.A.
		Zone 2		
Pine Ridge	N.A.	N.A.	N.A.	N.A.
Temora	N.A.	N.A.	N.A.	N.A.
Grong Grong	N.A.	N.A.	N.A.	N.A.
Corowa 1	N.A.	N.A.	N.A.	N.A.
Corowa 2	N.A.	N.A.	N.A.	N.A.
Corowa 3	N.A.	N.A.	N.A.	N.A.
Bendigo	N.S.	N.S.	N.S.	N.S.
		Zone 3		
Tasmania	C	N.S.	N.S.	N.S.

↑ A significant linear increase with respect to increments in air temperature.

↓ A significant linear decrease with respect to increments in air temperature.

C Statistically significant quadratic or cubic relationships.

N.S. No significant trends.

N.A. Data not available.

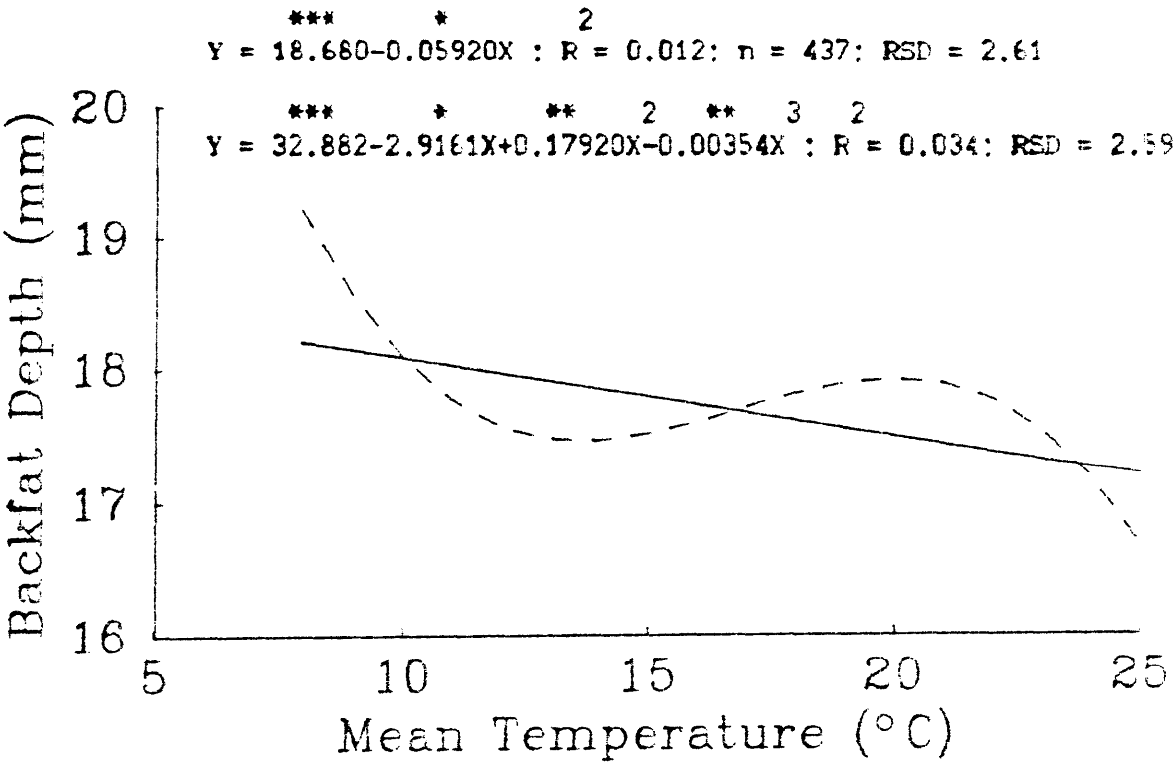

Figure 14. Backfat Depth (P2) of pigs in zones 1+2+3 as related to the mean monthly temperature.

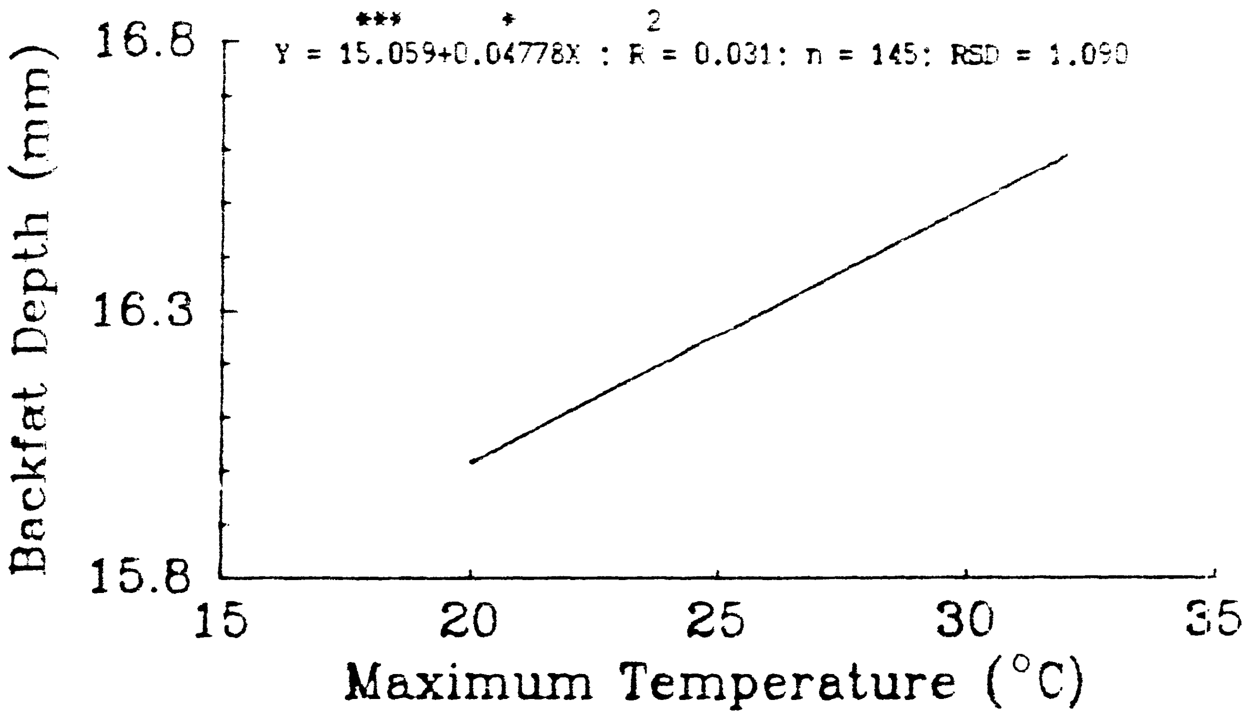

Figure 15. Backfat Depth (P2) of pigs at Gatton, Queensland, as related to the mean monthly maximum temperature.

with increasing maximum (Figure 15; $P<0.05$), minimum ($P<0.05$) and mean ($P<0.05$) temperatures.

Plate 1. An intensive piggery with galvanized sheet-metal pen partitions.

2.4 Discussion

The data obtained in the present study came from producers situated in a wide range of climatic conditions, and significant differences between them were confirmed by homogeneity tests. As well as climatic influences, differences in management practices (see Plates 1-3) are also likely to have contributed to between-farm differences.

The overall decline in DRG with increasing ambient temperature observed in this study was approximately 10 g/d/°C increment. The fact that the rate of decline of DRG within zone 1 was slightly higher than that in zone 2 may be attributed to differences in the respective climatic conditions. Although maximum temperatures in zone 2 was as high as in zone 1, minimum

Plate 2. An intensive pig unit with steel mesh partitions.

Plate 3. An extensive pig production system.

temperature and relative humidity were much lower. It has been shown that cool night temperatures may allow compensatory physiological adjustments to take place (Andrews and Noffsinger, 1956), while low humidities will impose less stress on pigs than high ones (Heitman and Hughes, 1949). Therefore, pigs growing during the hot season in a place where humidity was low during the hottest part of the day and where cool nights occurred could be expected to perform better than at first suggested by a consideration of maximum temperatures alone.

Estimates of the thermoneutral zone of pigs in zone 1 (16 to 21° C) were also slightly higher than those of pigs in zone 2 (14 to 20° C). Both of these values are slightly lower than those reported for pigs in U.S.A. (Mangold *et al.*, 1960; Morrison, Heitman and Bond, 1969).

Results from the present study support earlier findings obtained under laboratory conditions where either the diurnal temperature variation was small (Holme and Coey, 1967) or where temperature was constant (Stahly and Cromwell, 1979) in that they show that pigs convert most efficiently at a maximum temperature of about 22° C. However under commercial conditions in the present study, where larger diurnal temperature variations existed (e.g. up to 15° C) the optimum mean temperature for FCR was found to be 16° C. The rate of decline in FCR as environmental conditions deviated from the optimum (0.01 kg/kg/° C) was, however, smaller than values (approximately 0.03 kg/kg/° C) calculated from the results of Holme and Coey (1967) and Stahly and Cromwell (1979).

Values calculated from the pooled data (all farms) indicate that P2 backfat depth declined at the rate of 0.01 mm/° C increase in mean temperature. This relationship, which is at variance with the reports of Fuller (1965), Sugahara *et al.* (1970) and Straub *et al.* (1976),could in part be due to the fact that the pooled data included that from farms in the temperate climatic zone of Tasmania where maximum temperatures were far less than those in zones 1 and 2. On the other hand, if these relationships were considered on an individual farm basis, especially in hot climates such as those of zone 1, it was observed that P2 increased significantly with each of maximum (Figure 15), minimum and mean temperature (Table 9) at the mean rate of 0.05 mm/°C rise. These apparently conflicting results could also be associated with differences in feed intake and rate of gain. Unfortunately, the data are not sufficiently detailed to allow these possibilities to be evaluated.

The relative importance of month of the year was far less than that of either maximum or minimum temperature (Appendix III) with respect to DRG. However, month proved to be more important than either maximum or minimum temperatures when both FCR and P2 were considered, especially at the within-zone level. Furthermore, maximum temperature was more important than minimum temperature in the case of DRG, FCR and P2 when the pooled data were considered. When both maximum and minimum temperature are taken into account concurrently then the results of the canonical analyses are consistent with those from the regression approach. In both cases DRG and P2 declined and FCR increased with increments in temperature.

Although significant relationships were established between individual biological and meteorological parameters it must be recognised that the biological parameters may in fact be influenced by either a single or a composite of meteorological parameters, since the latter are interrelated. The influence of maximum temperature, for example, may be modified by the minimum temperatures experienced, as pigs have been shown to acquire some degree of adaptation (Morrison, Heitman and Given, 1975) when subjected to fluctuating environmental temperature regimes. Thus mean temperature alone might be expected to be a less sensitive parameter since this value does not incorporate any measure of temperature variability. Similar mean temperatures could be recorded under both virtually constant and widely fluctuating temperature regimes. Furthermore, in practice, maximum and minimum temperatures normally occur for only short periods of the day. Pigs may thus be considered to have been effectively subjected to environmental temperatures that were between the maximum and minimum values actually recorded. One way to overcome this problem is to utilize the "degree-hour" approach whereby environments are classified by the number of degree hours (per day, per week etc. as appropriate) spent either under or over a specified temperature. Such precise meteorological data were unfortunately not available in the present field survey.

The meteorological data used in the present analyses were not shed temperatures (since they were not available), and in practice shed temperatures would be expected to be higher than "outside" ones. At the same time, daily variations in shed temperature would be smaller than in that "outside".

Further study is needed of the effects of environment on the growth performance of pigs under commercial conditions taking into account actual shed temperatures as well as humidity, wind velocity and solar radiation, all factors which have been shown to influence growth under laboratory conditions (see II-2.2). A standard diet applied to all piggeries under investigation in the various climatic zones would help to reduce any differences that might be attributable to dietary effects. Such work will necessarily be expensive and time consuming since commercial pig producers do not, in general, appreciate the degree of precision and standardisation needed for this type of research and do not possess many of the necessary meteorological instruments.