Genetic management of pig adaptation to tropical farming systems

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PREFACE.

This text is a summary of my research activities. This work was mainly carried out with the support of my INRA colleagues from the animal production research unit (URZ) and the tropical platform for animal experimentation (PTEA).

« Tout biten vin biten paapot on biten » is a Creole proverb from a famous Guadeloupean artist Lukuber Séjor. That means everything becomes something because of the realization of a first thing. I have often quoted these words, because my research studies are a continuation of previous studies. Since 2003 (the beginning of my Ph.D studies), I took the URZ's transdisciplinary train in which geneticists, nutritionists, zootechnicians, physiologists work together to improve tropical animal production in a sustainable way. In other words, I have been privileged to stand on the shoulders of scientists, like G. Alexandre, H. Archimède, N. Mandonnet, A. Menendez-Buxadera, M. Mahieu, M. Naves, D. Renaudeau and animal research technicians such as C. Anaïs, K. Benony, D. Beramice, B. Bocage, M. Bructer, E. Despois, M. Giorgi, the late G. Gravillon, F. Silou, and the experience has been profoundly rewarding.

In the whole document, I will quote my scientific publications in priority (accepted or submitted) as **[A or B or C - number]**[1] corresponding to my papers in order of publication. For unpublished works, I will quote the papers presented at conferences as **[F or G - number]**[2] or MS thesis that I have supervised **[H number]**. The complete list of my research studies is presented in the Appendix 1.

[1] A : research articles published in journals indexed ESI ; B : research articles published in journals not indexed ESI; C: review articles

[2] F: invited conference; G: short communications

Chapter One: INTRODUCTION.

1. Context.

Ignoring food waste, enough food is currently produced per capita to feed the global population (FAO, 2012). Increasing food production is nevertheless important as 60% more food will be needed by 2050 for food security of human population of more than 9 billion (Porter et al., 2014). Even if meat consumption began to decrease in some areas in the North, the global demand for livestock products is expected to be twice that of today, particularly in developing countries (Delgado et al., 1999). According to the FAO statistics, more than 50% of world pig production occurs in tropical and subtropical regions (Figures 1 and 2), particularly in East and Southeast Asia, and it is predicted that these areas will continue to support future growth (Bruinsma, 2003). However, the hot climatic environment is one of the main limiting factors in pig production, mainly due to the low sweating capacity of pig compared with the most livestock species.

Meanwhile, the climate is changing. According to the modelling results of the International Panel on Climate Change Assessment Report 4, global temperature is expected to increase in the 21st century from 1.1 to 2.9°C for a "low scenario" and of 2.4 to 6.4°C for a high scenario" (IPCC, 2007). Little is known on the impact of climatic change on livestock animal productivity (Thornton et al., 2009; Nardone et al., 2010). Climate change may indirectly impact on pig production systems by acting on feedstuff for pigs (decreasing soil fertility, water scarcity and their repercussions on the availability of dietary ingredients) and directly with heat stress. It can be safely suggested that heat stress-related issues in pig production will increase in the future, with negative effects on animal health and welfare, reproduction and production.

In tropical and subtropical regions, pork production is based on a variety of farming systems (Robinson et al., 2011). These farms are situated between two extremes. The first extreme is specialized industrial and landless farms with high pig density. These pig production systems are based on the use of a limited number of selected commercial breeds or lines with high genetic potential for high growth and reproduction. The second extreme is small family farms with indigenous and/or crossbreeds reared in low input conditions. In simplified terms (see caricatural, but just to fix ideas), there are two opposing logics of production. "Do to" maximize the pig output/input ratio in industrial systems vs. "Do with" the available biomass from the farm or neighbouring farms to limit inputs in non-conventional systems. These two logics are clearly not mutually exclusive, and can in some cases support each other. Nevertheless, pork products from all production systems should suit with the societal demand for more environmental-friendly farming systems (reducing the carbon footprint), higher meat quality (sanitary, nutritional, technologic and organoleptic) and higher animal welfare (Gerber et al., 2013).

In industrial pig systems, farm management is technically well controlled. Scientific research efforts are predominantly oriented toward the design and the evaluation of i) solutions to mitigate the adverse effects of pig production on the environment (waste management) and ii) solutions to mitigate the adverse effects of the environment (disease challenge, climate …). Non-conventional pig systems are highly dependent on the availability of the biodiversity in their environment. Scientific research can help for a better understanding of the functionality of the whole system for which pig production system is only one element **[A18]**. The purpose is to propose solutions optimizing the integration of available crop and livestock resources, and thus limiting the inputs. Taking into account the diversity of economy, climate, environmental and social constraints that exist in tropical and subtropical regions, the development of the pig production cannot be completely ensured by a simple transposition of the technologies used in temperate countries **[C7]**. In fact, in hot areas, adaptive capacity of animal and the farming systems to multiple climatic and biotic stresses represents the key tool to improve the sustainability of the production systems **[C2].**

2. My position at INRA.

The aim of my research unit is to promote sustainable animal production in the tropics within an agroecological perspective. Until 2014, our research project was divided in 3 scientific work packages: i) WP1: animal's adaptation to environmental constraints ii) WP2 :Multicriteria evaluation of feedstuff and iii) WP3: Zootechnical, agronomic and environmental evaluation of livestock production systems (Figure 3). The URZ's project was validated by the French evaluation agency for research and higher education (AERES[3]), during the collective evaluation in 2009. More generally, our research activities belong to strategic plan of Animal Genetics (GA[4]) and Animal Physiology and Livestock Systems (PHASE[5]) Divisions of the French National Institute for Agricultural Research (INRA).

My first work at INRA started in 2002 for my Master's thesis. I worked on modelling the growth curve of Creole cow, under the supervision of M. Naves and A. Menendez-Buxadera. I graduated with a Ph.D in animal genetic and adaptation from INA P-G(now AgroParisTech) /INRA in 2006, working on the analysis of factors affecting reproduction of sows in tropical humid climate, with David Renaudeau and Jean-Pierre Bidanel as supervisors. I was then recruited as a research engineer in August 2006 in the INRA URZ.

Since 2006, my research topics are about i) the characterization of genetic variability of heat adaptation in pig and ii) conception and evaluation of innovative pig production systems for

[3] http://www.aeres-evaluation.com/

[4] Animal Genetics Division : http://www.ga.inra.fr/en/

Strategic plan : CT1 : The genome: fine structure and functional organization; CT2: The animal: genetic levers for innovative and sustainable farming; CT3: Animal populations: characterization, management and optimization.

[5] Animal Physiology and Livestock Systems Division: http://www.phase.inra.fr/en/

Strategic plan : CT1 : feeding resources; CT2: Adaptation; CT3: Production; CT4: Systems the tropics (Figure 4). My activities belong to the workpackages WP1 and WP2. The results of my research activities are described in the chapter 2 (genetic variability of heat adaptation in pig) and in the chapter 3 (valorization of pig's adaptation in non-conventional farming systems). A third chapter deals with the general conclusions and future perspectives of my research activities.

Chapter Two: GENETIC VARIABILITY OF HEAT ADAPTATION IN PIG.

1. Introduction.

Heat stress can be defined as the magnitude of environmental and metabolic loads on the animal, for which the animal cannot dissipate an adequate quantity of heat to maintain homeostasis with minimal performance losses. Heat stress impacts pig performance and welfare and thus the economic viability of pig production. For example, in the USA, heat has been estimated to increase sow mortality by 0.01 to 0.36% and to increase growing pig mortality by 0.02 to 0.6%, leading to a global yearly economic loss around $300 million (St-Pierre et al., 2003). In fact, genetic selection performed in optimally controlled conditions, has allowed significant improvement in reproductive traits and lean tissue growth rate (Costa et al., 2010; Merks et al., 2012). Thus, metabolic heat production of pig had increased with the improvement of production traits. These improvements were achieved at the expense of adaptive capacities of animals. Consequently, it is suspected that the animal's ability to cope with high ambient temperatures has decreased (van der Waaij, 2004). In a meta-analysis, we suggested that genetic selection has reduced the growing pig's ability to cope with thermal stress **[A14]**.

There is a great amount of research to propose solutions for mitigating heat challenge of pigs subjected to acute or chronic heat stress[6]. Several solutions are available, such as altering the environmental (cooling options) or feeding management (changes in diet composition / distribution) **[C8]**. However, these mitigation strategies come at a high cost and these expenses may not be economically and environmentally advantageous in many tropical situations. In a context of internationalization of pig selection and of increased occurrences of economic losses due to heat stress, the genetic selection of heat resilient[7] (or heat tolerant) genotype is a promising long term option **[G5]**. The improvement of heat adaptation of pigs by genetic selection assumes that there is a genetic component of heat tolerance. In other words, ability to maintain performance in heat-stressful conditions is at least partly inherited.

[6] Acute heat stress corresponds to a stressful event such as summer heat waves in temperate countries. Chronic or long-term heat stress is during the lifetime of the animal, such as constant heat challenges occurring under tropical and subtropical conditions.

[7] Heat resistance can be assimilated to the ability of a pig to develop thermoregulatory responses to mitigate the effects of heat on his system or to survive an acute heat stress. Heat resilience or heat tolerant pig is able to maintain his production level under or thermal stress.

At INRA-URZ, our first studies, performed between 2006 and 2014, on the genetic pathway of adaptation to heat in pig, aimed at i) determining biological relevant and accurate standardized phenotypes to characterize heat tolerance capacity, ii) characterize the genetic variability of adaptation to heat (between and within breed) using a classical quantitative genetic approach; iii) defining and performing an experimental design for identifying and mapping QTLs for heat tolerance, iv) conceiving and evaluating breeding schemes with heat tolerance as a breeding objective.

2. Biomarkers for thermotolerance in pigs.

2.1. Thermoregulation in pigs.

To describe the phenotypes we have chosen to discriminate thermotolerance variability, we should have to specify the thermoregulation responses.

Pigs are homeothermic animals as they can keep deep body temperature relatively constant, within narrow limits despite wide variations in climatic environment. Thermoregulation is the physiological function allowing the balance between heat production and heat loss mechanisms. The relationship between ambient temperature, heat production and heat loss is schematically illustrated in Figure 5. Illustrative values of critical and rectal temperatures are given. There are based on meta-analysis on lactating sows **[A14]** and on growing pigs **[G38]**, and from our results. These temperatures vary greatly, depending on numerous factors such as breed, body weight and composition, diet management, group size, temperature by humidity interactions.

Pigs can lose heat by conduction, convection and radiation (sensible heat loss), and by evaporation (latent heat loss). In the zone from C to D (the thermoneutral zone, Figure 5), pig metabolism (and heat production) is relatively constant. When the ambient temperature increases above D, heat transfer by sensible way becomes ineffective due to the reduction of the gradient between skin and ambient air. Pigs rely mainly on their evaporative heat losses to maintain a constant body temperature, by increasing respiratory rate. The increase in panting, metabolism and core body temperature may be different between animals. Hence, if there is genetic potential for breeding for heat tolerance, pigs or stains with higher C, D, E or F values could be theoretically obtained, resulting in an increased tolerance to heat stress (Kanis et al., 2004).

2.2. Phenotypes in lactating sows reared in tropical humid conditions.

The works on noninvasive monitoring of phenotypic parameters for heat tolerance were first realized on lactating sows, and more recently on growing pigs (see section 2.3). All measurements and observations on animals were operated in the Tropical Platform for Animal Experimentation (INRA-PTEA) experimental farm in Guadeloupe (16°N latitude, 61°W longitude). Animals were housed in a semi-open piggery in which daily climatic variations followed those of outdoor conditions[8] (Figures 6a and b). The daily fluctuation of ambient

[8] Inside climatic records (ambient temperature and relative humidity) are continuously recorded every 30 min in each room of the experimental pig farm using a Campbell weather station. Outside climatic records are from a closed Campbell weather station within 50 m of the experimental farm

temperature showed that in our experimental conditions, lactating sows were heat-stressed most of the time, as few inside temperature records were lower than 22°C. Furthermore, relative humidities are more often greater than 80% (Figure 6b). It is well recognized that high relative humidities emphasize the negative impact of high ambient temperature on pig by limiting the capacity of evaporative heat losses (Huynh et al., 2005; Renaudeau, 2005). For this reason, a thermal humidity index (THI) was calculated. The THI allows combining in one function the effect of temperature and relative humidity and their interaction.

In regards to phenotyping, we sought to define the most appropriate phenotypes for estimating the genetic variability of heat tolerance. In other words, the main purpose was to obtain biological relevant parameters technically easy to record routinely in our experimental conditions. Some measurements (such as rectal temperature) have been already performed routinely on lactating sows since 2002. We have added others phenotypes such as skin temperature or respiratory rate, and other stages of measurements.

Physiological studies on the effects of hot temperatures on thermal adaptation of growing pigs were performed by my colleagues, particularly D. Renaudeau **[A7, A12]**. Their experiments have been a source of information for finding relevant phenotypes for the genetic studies. They have shown that several macro-biomarkers either directly or indirectly related to heat production or heat loss, and core body temperature can be measured (see also the review of (Renaudeau et al., 2004). Table 1 presents the list of macro biomarkers of heat tolerance used. Rectal temperature is an indicator of core body temperature, which is the result of the thermoregulation process. Skin temperatures measured in several sites are indicators of sensible heat loss. More precisely, with rectal, skin and ambient temperatures or THI, a thermal circulation index[9] can be calculated as an indicator of blood flow to the skin to promote sensible heat loss **[A7]**. Respiratory rate is an indicator of latent heat dissipation. Finally, the variations of traits of important economic interest according to the heat load, such as reproduction and production traits (growth rate, feed intake) are indicators of heat resilience.

However, these physiological studies were performed in climate-controlled conditions (when climatic environments are monitored and heat stress conditions were imposed), and compared a standard situation (thermoneutrality) to heat stressed ones. The main challenge was how to assess whether a parameter was a good indicator of sensitivity to heat stress when there is no “standard situation” corresponding to the thermoneutral zone. Hence, a simple transposition of the phenotypes recorded in physiological studies in climate-controlled experiments and for short term heat load could not be realized for quantitative genetic studies.

We first standardized phenotyping of lactating sows. Lactating sows are particularly sensitive to heat stress, due to their high metabolic heat production for milk production. We hypothesize that longitudinal recording gives more accurate information to characterize the variability of heat tolerance. Hence, records were performed on thermoregulatory responses along the lifetime of the animal, combining with reproduction performances and records of

[9] In this document, we used the following formulae for the thermal circulation index : TCI = (CT – THI) / (RT – CT) where CT is the skin temperature, THI is the thermal humidity index and RT is the rectal temperature.

environmental conditions (ambient temperatures, humidities). We have taken into account two time scales: within a day and during lactation. Figure 7 summarizes the measurements performed on lactating sows from 2006 to 2012. Measurements on thermoregulation were performed at nine time points during lactation in order to follow the concomitant evolution of thermoregulatory responses with energy intake and milk production. Thermoregulatory responses have been measured twice daily at 07:00 h and at 12:00 h, corresponding to periods covering the lowest and highest daily ambient temperature. The deviation of thermoregulation parameters measured at 12:00 h from those measured at 07:00 h, when ambient temperature and metabolic activity are low, can be viewed as an indicator of the daily variation in thermoregulation effort. We have shown that the most discriminating daily period (i.e. maximum range) for thermoregulatory variation is between 04:00 to 0700 h and 19:00 to 23:00 h (Figure 8a, **[H1]**), in relation with the hourly feed intake (Figure 8b, **[A5]**) and the circadian rhythm of core body temperature. Even if the daily amplitude of variation of thermoregulation responses is underestimated, the period of measurements at 07:00 and 12:00 h is a compromise between physiological responses of sows and labor management on the experimental farm.

At the lactation scale (from 0 to 27 days), our studies have shown that the average daily rectal temperature of lactating sows increased in the beginning of lactation, remained relatively constant thereafter and decreased after weaning (Figure 9). It is hypothesized that the increase of rectal temperature during lactation is a direct consequence of the increase in metabolic heat production related to increase in energy and protein intake and milk synthesis (Williams et al., 2013). Likewise, the decrease in rectal temperature after weaning reflects a decline in heat production related to the drop in feed intake and the interruption of milk synthesis **[A4, A6]**.

The effect of high ambient temperature on performance of lactating sows is well known in the literature but less documented in tropical humid conditions. The analysis of the effect of tropical humid climate on zootechnical performance of lactating sows was mainly performed during my PhD work **[A1, A2, A3, A4, A5]** and the phenotypic analysis of thermoregulation parameters was after 2006 **[A6, A24]**. Figure 10 summarizes the effect of thermal humidity index on lactating sows. The results had shown that average daily feed intake of lactating sows is markedly reduced by on average 16% when the average THI during lactation exceeds 23.5°C (Figure 10a). In our experimental conditions, high THI during lactation had poorly affected milk composition **[A4]**. Consequently, the reduction in milk production results in a reduction in litter body weight (BW) gain and piglet BW at weaning (Figure 10b). Higher THI also results in an increase in mobilization of body reserves (Figure 10c), which may impair reproduction after weaning **[A3]**.

The effect of THI on thermoregulation parameters in lactating sows are presented in Figure 11. Higher THIs (greater than 23.5°C) have resulted in a reduction in the thermal circulation index (Figure 11a) of lactating sows whereas the respiratory rate increased (Figure 11b). These results underline the inefficiency of sow to lose heat by sensible pathways when THI during lactation exceeds 23.5°C. The role of latent pathway (i.e respiratory evaporation) becomes then more important. Rectal temperature increased with THI (Figure 11c), with an average increase of 0.13°C per degree of THI. From a meta-analysis, Dourmad et al. (2015)

[G38] found a curvilinear relation between the increase in rectal temperature and ambient temperature and reported an increase in rectal temperature of 0.07°C per degree of ambient temperature. As previously commented, it can be suggested that, in tropical humid conditions, the relative humidity emphasizes the sensitivity of lactating sows to heat stress.

Furthermore, at daily scale (Figure 12), the change in TCI from 07:00 to 12:00 h (Figure 12a) significantly decreased in lactating sows raised in high THI conditions (corresponding to average THI greater than 23.5°C). This is in relation with a narrowed variation window of daily THI between 07:00 and 12:00 h (range of 0.8 °C) compared with a range of 1.8°C for lactations occurring on average THI lower than 23.5°C. The effect of the average THI during lactation was not significant for respiratory rate deviation ($P > 0.10$). Consequently, the change in rectal temperature from 07:00 to 12:00h (Figure 12b) was most pronounced for lactating sows in high THI conditions.

2.3. Phenotypes in growing pigs reared in tropical humid conditions.

Based on the phenotypes on lactating sows obtained in semi-open conditions **[H1, H2]** and the studies of colleagues on growing pigs in controlled conditions **[A7, A12]**(Renaudeau 2005; Renaudeau et al., 2006; 2007), we carried out studies aiming at standardizing phenotypes of heat tolerance in growing pigs. The standardization is crucial, particularly when measurements are realized in different conditions, which is the case for the experimental design both in tropical and temperate conditions for mapping QTLs related to heat tolerance (see section 5 of Chapter Two).

In our studies, the standardization of macro-phenotypes measured on growing pigs was performed on pigs raised at the experimental herd of INRA-PTEA with half of pigs housed in rooms with automatic feed dispensers and other pigs fed together **[G15, H4]**. The aim was to evaluate to what extent the phenotyping of thermoregulation traits is routinely feasible in semi-open conditions in order to produce fundamental information on genetic variability of heat tolerance in growing pigs. To our knowledge, studies on thermoregulatory response of growing pigs raised in tropical humid climate and in similar conditions to commercial ones are rare. This is mainly due to the fact that it is difficult to measure thermoregulation traits on animals living in groups. Our main results on the effect of the tropical climate are summarized in Table 2. They are in accordance with common response of pigs during heat stress from climate-controlled room (Renaudeau 2005)**[A7]**. A reduction of feed intake was observed when THI was high (more than 27.7°C). This reduction of appetite is associated with a reduction of the number of meals and of the ingestion time. In this way, growing pigs reduce their metabolic heat production. An important individual variability was found for thermoregulatory responses, as the variance accounted for by differences between pigs represented on average 90 % of the total variance **[G15]**. The experience showed that only body temperature can be easily recorded when animals are isolated during the measurements of body weights and backfat thickness. Hence, in grouped growing pigs more than in isolated lactating sows, measuring of thermoregulation traits becomes a limiting factor. That reveals the necessity of methodologies improvements to record relevant individual thermoregulatory parameters in the pig raised in groups.

As a summary, the originality of our results is in the characterization of the effect of tropical humid climate both on zootechnical performance and thermoregulatory responses of pigs raised in conditions that are comparable to farming production ones. Our studies have shown that there is an important individual variability in thermoregulation for which the genetic component and the relationships with production traits must be appreciated. These studies have also shown the difficulty of analyzing heat tolerance when we would like to take into account other traits than production traits. We also highlighted some technical obstacles for phenotyping of heat tolerance for genetic selection. We need to develop and standardize non-invasive methods that can be used routinely (e.g. methods of optical type, of imaging treatment). It is also necessary to investigate and validate biological and genetic markers that are able to early detect the animal's capacity to tolerate heat. We hope that new phenotypes both from imagery technologies (infrared camera, high throughput image treatments) and omics technologies will improve the accuracy of phenotypes. For instance, fine phenotypes are becoming more and more available with the emergence of functional genomic technologies (particularly metabolites and single-nucleotide polymorphisms (SNP)). That gives us the opportunity for identifying micro-phenotypes (e.g. QTLs) that would be good predictors of genetic values of pigs for heat tolerance.

3. Between breed variability.

Genetic differences between breeds or lines in response to heat stress have been reported in several species such as cattle (Burrow and Prayaga 2004; Hayes et al., 2009), poultry (Mignon-Grasteau et al., 2015) or pigs (Bloemhof et al., 2008 and 2013). To our best knowledge, little has been published in differences in heat tolerance between tropical and mainstream pig breeds. Most of local pig breeds are from tropical and subtropical areas (FAO, 2007), but many of them are not well characterized.

In our experimental conditions, the between breed variability for heat tolerance was studied by characterizing the effect of tropical humid climate on the performance of Large White pig compared with the Creole pig (local breed). In tropical and subtropical areas, microevolution had promoted the emergence of breeds with a high ability to cope with heat stress **[C6]**. The Creole pig has a unique combination of genes from European breeds brought by European colonists during the 16st century (FAO, 2007). This breed has never been genetically improved and it shows a high level of genetic variability. On the opposite, the Large White pig is a major maternal breed used in commercial breeding schemes worldwide and selected from more than 30 years on lean tissue growth rate and reproductive capacity (Whittemore, 2007). For instance, Figure 13 shows the large variation in backfat thickness at farrowing measurements taken from a population of Creole sows as compared with the variation of

Large White sows. This breed is then a highly productive breed but theoretically less heat tolerant than Creole breed.

At INRA-URZ, the most recent studies on the effect of heat stress (short-term in climate-controlled conditions or long term from comparison of warm to hot seasons) on Large White and Creole breed were performed both on functional **[A15, A21]** (Renaudeau 2005; Renaudeau et al., 2006 and 2007) and production **[A4, A5, G39]**(Renaudeau et al., 2006) traits (Table 3). I have mainly contributed on the studies on lactating sows (Figure 14).

3.1. Lactating sows.

The results showed that the effect of high THIs during the hottest season[10] (an average THI of 25.1°C) on reducing feed intake were accentuated in Large White sows (-20 %) compared with Creole sows (-14%) **[A4]**. This result is likely related at a lower metabolic heat production in CR sows due to their lower lactating performance. Furthermore, we have shown that the amount of feed consumed during the hottest period of the day (on average THI of 29.0°C) was 13 % in Creole sows against 3 % in Large White sows **[A5]**. This higher ability of Creole sows to consume during the hottest periods of the day could go to the direction of better heat tolerance. The weaning to estrus interval of Creole sows was not affected by the season (on average 4.7 days), unlike Large white sows (4.7 days after an average THI during lactation of 23.5°C vs. 5.7 days after an average THI during lactation of 25.1°C, unpublished results). Whatever the breed, the high THIs lead to an increase in the weaning to conception interval. However, the effect is much less marked in Creole sows (+2 days) than in Large White sows (+9 days). This increase of unproductive period under heat stress could be caused, at least partly, by the greater body weight losses of lactating Large White sows (+11%) than Creole sows (+3%) [**A4]**.

Regarding thermoregulatory responses, high average THIs during lactation caused higher increase of rectal temperature (Figure 15, **[A6]**), skin temperature (Figure 16) and respiratory rate (Figure 17) in Large White than Creole sows, suggesting better physiological adaptation of Creole sow to heat stress. Moreover, we observed higher variation within Creole sows than within Large White ones, illustrating the high variability of an unselected breed compared with a selected one.

3.2. Growing pigs.

Previous studies on growing pigs had shown that the effect of season or short-term heat stress on production performance and thermoregulatory responses were more important in Large White than Creole pigs (Renaudeau 2005; Renaudeau et al., 2006). Our results on between variability of heat tolerance in growing pigs were mainly a "by-product" of our studies aiming at comparing the effect of rearing system (outdoor vs. indoor, conventional vs. "local" diet)

[10] The hot season is between May to October (on average 26.0 °C and 85 %, for outside ambient temperature and relative humidity, respectively) and the warm season is from November to April (on average 23.8 °C and 85 %, for outside ambient temperature and relative humidity, respectively)

on the production performance and the body temperatures of Large White and Creole growing pigs (see Section 4 of Chapter Three). In these studies, outdoor climatic conditions were characterized by a higher average THI of 25.3°C compared with the average THI of 23.6°C in indoor conditions (Table 3). Regarding growing pigs fed with the same diet, we observed that whatever the rearing conditions (outdoor or indoor) skin and rectal temperatures were significantly higher in Large White (37.0 and 39.9°C) than in Creole pigs (36.0° and 39.5°C), suggesting that Large White growing pigs are more heat stressed. However, skin temperatures in outdoor pigs were higher than in indoor pigs (+2.4°C, whatever the breed). Since no breed difference was observed in rectal temperature of outdoor pigs (39.9°C), one may suggest that both Creole and Large White growing pigs suffer from heat in these outdoor experimental conditions. Regarding production performance, we observed a higher reduction of growth rate in Large White (-36%) than Creole (- 18%).

As a summary of between breed variability of heat tolerance, as expected, our studies confirm that Creole breed is better heat tolerant than Large White breed. Indeed, the decrease in the production traits of Creole breed during high THIs were less pronounced than for Large White breed, showing that Creole breed have higher critical temperatures values. This physiological adaptation to heat stress could be partly explained by a lower metabolic heat production due to a lower productive potential. Furthermore, our studies also show higher ability to dissipate heat in Creole breed, particularly in lactating sows. Since heat loss capacity is generally less related to production traits, one may suggest that in case of good inheritance, selection made simultaneously for high heat loss and production traits could be more feasible than selection for production and against heat production. In this context, the use of natural resistance or resilience of tropical breed in breeding selection towards more heat tolerant pigs might be advantageous.

4. Within breed variability.

In contrast to production traits, the inheritance of traits related to heat tolerance has been poorly described. Most of recent research studies on the genetic variability of heat stress have investigated on genetic component of economic important traits as a function of head load. To our best knowledge, little information is available on the inheritance of thermoregulation traits in pig. In other species, such as cattle or poultry, rectal temperature is the only thermoregulation traits for which heritability was accurately estimated (Table 4). However, heat resistance and heat tolerance are complex traits for which rectal temperature is an indicator of only one aspect, i.e. the result of the whole thermoregulation process. Indicators of sensible and latent heat loss abilities or low heat production capacity are also important.

Our studies on the within breed genetic variability of heat tolerance were realized on Large White lactating sows, based on a database with several thermoregulation traits observed since 2002 (see section 2.2 of this Chapter). We have first studied the pattern of variance components according to the stage of lactation **[H7]**, and thereafter we have considered the average performance during lactation. We have also quantified the genetic variability of lactating sows' production traits, and how they are correlated with the genetic variability of thermoregulation traits **[A24, G4]**.

4.1. Genetic variability of traits with longitudinal records according to the stage of lactation.

Heritabilities as function of stage of lactation, for thermoregulation traits and average daily feed intake are presented in Figure 18. They are calculated from the variance-covariance estimates in random regression animal models **[G3]**. Heritabilities for rectal temperature and respiratory rate were higher than for skin temperatures. Heritabilities were generally lower during the first periods of lactation; they increased after and remained fairly constant afterward. To our knowledge, these are the first results reported in pig. Furthermore, the curve of heritability for feed intake followed the sow's feed consumption curve during lactation. This in accordance with other studies (e.g. Hermesch, 2007). However, the estimates of heritability of feed intake according to the period of lactation are higher than the range of results reported in the literature (range between 0.02 to 0.20). Estimations of genetic parameters at the beginning and the end of the trajectory obtained from random regression analysis are generally over or underestimated (Huisman et al., 2002; Fischer et al., 2004). Ignoring these values, from the results presented here, it seems that the traits studied can be treated as the same trait throughout periods of lactation, with fairly constant heritability and variance. Indeed, as an illustration of the pattern of variance, variance components of rectal temperature during lactation, measured at 12:00 h are presented in Figure 19. Similar patterns were observed for the other traits. Nevertheless, largest heritabilities and genetic variances were estimated in mid-lactation. In a practical point of view, it seems that measuring thermoregulation in mid-lactation and during the afternoon should be the best period to discriminate heat tolerant animals.

4.2. Genetic variability of average performance in lactation.

Considering the small size of our dataset, it was not possible to estimate the genetic components of traits as a function of THI values, as we have done for phenotypic analysis (see Section 2.2 of this Chapter). The REML estimates of variance components of the average lactating performance and thermoregulatory responses were obtained using multi-traits animal models.

At the average lactation level, thermoregulation traits are heritable which suggest that thermoregulation capacity can be changed by selection (Table 5). To our knowledge, little has been published on the genetic of thermoregulation traits in pigs. The estimated values are around 0.35 ± 0.10 for the average rectal temperature, skin temperature or respiratory rate during lactation. The heritability estimate of rectal temperature in our study was in line with the range of estimates (0.11 to 0.36) reported in other species (Table 4). Thermoregulation is a homeostatic process, so that internal temperature remains stable and relatively constant. So, what could be genetic improvement for a better thermoregulation? The aim of selection for a shorter or a higher rectal temperature should not be viewed to move the average core temperature (for instance from 38.7 to 39.7°C), but rather to decrease the number of heat-stressed sows (i.e. reducing the variance than changing the mean). At an animal level, that corresponds to pig with a better regulation of body temperature during heat stress.

The heritability estimate of the average daily feed intake (ADFI, 0.25 ± 0.08) was in agreement with estimates obtained in studies conducted in temperate conditions (Bergsma and Hermesch, 2012; Gilbert et al., 2012). However, the h^2 value for ADFI is greater than the average value of 0.08 ± 0.04 obtained by Akanno et al. (2013) from meta-analysis of studies realized in the tropics. The heritability estimate of litter BW gain and sow BW loss during lactation were moderate (0.31 ± 0.09 and 0.20 ± 0.07). These values are in accordance with those reported in Rydhmer's review (2000).

The genetic correlation between average daily feed intake (ADFI) and sow proportion body weight (BW) loss during lactation was favourable (-0.80 ± 0.14) suggesting that sows with a high genetic merit for ADFI showed genetically lower BW loss during lactation. This correlation was expected because a genetic increase of sow voluntary feed intake reduces the utilization of maternal body reserves to support high nutrient requirements for milk production (Eissen and Kemp, 2000). Litter BW gain is genetically favorably related to sow's ADFI (rg = 0.25 ± 0.11) and more strongly related to sow's BW change (rg = 0.59 ± 0.20). High litter BW gain which partly reflected high milk production, leads to high BW change during lactation as nutrient requirements during lactation are rarely fully covered by feed intake. The phenotypic and genetic correlations between thermoregulation traits were positive and high, reflecting the physiological link between these parameters (i.e. heat transfer from the core-to-skin). This result is consistent with the results obtained by Martins et al. (2008).

As reviewed by Renaudeau et al. (2004), there is a moderate to strong negative phenotypic correlation between rectal temperature and production traits in many species, but with large standard errors due to the limited number of animals in most experimental designs. In our study, no significant correlations between body temperatures and performance traits were reported. However, the phenotypic and genetic correlations between feed intake and respiratory rate were significantly different from zero (between 0.27 and 0.35), meaning that sows with higher feed intake would be the ones with the greatest respiratory rate.

As a summary, our studies provide estimates of heritability of thermoregulation traits in lactating sows that were previously poorly described in the literature. A low to moderate genetic variability is observed in the various component of thermoregulation. The results showed that thermoregulatory responses such as rectal temperature or respiratory rate are heritable; suggesting that selecting for better thermoregulation is possible. Our work has also shown the limits of such experimental studies with a small dataset (329 sows with measurements). Indeed, we have found a low accuracy of the genetic associations of thermoregulatory parameters with production traits such as sow feed intake or litter growth rate, likewise studies performed in other species. The estimate of thermoregulation parameters could be improved by analysis of more records. As with other complex traits, large numbers of genes are probably involved in heat tolerance. The combination of classical quantitative genetics with the knowledge more and more accurate of the pig genome, will allow better deciphering heat tolerance in pig.

5. Towards the identification of major heat tolerant genes.

To our knowledge, QTLs influencing heat tolerance has been poorly identified in pig. In other species, there are successful examples, such as QTLs for body temperature in the Japanese quail and in chicken (Minvielle et al., 2005; Nadaf et al., 2009) or in dairy cattle (Dikmen et al., 2013). With the availability of pig genome sequences, the new area of genome technologies increases the feasibility of identifying a very large numbers of polymorphisms (SNPs) that would predict some of the genetic variation of heat tolerance traits, and that allows a better understanding of underlying mechanisms.

Since 2008, we are developing collaboration between geneticists, physiologist and molecular biologist from different INRA research and experimental units[11]. We aim at identifying QTLs influencing the variability of heat tolerance traits and at better understanding of the physiology and molecular basis of heat tolerance. This project is a part of the ANR-BIOADAPT program (Adaptation: from genes to populations: genetics and biology of adaptation to stresses and disturbances, Edition 2011). The project is formalized into the PigHeaT project (Adaptation to heat in pig production: the genetic pathway)[12]. The animal production and the measurements in the experimental farms are now achieved but the genotyping and omics profiling are still in course and thus QTLs detection is not yet realized. Consequently, I would like to lay stress on the experimental design and the first results.

5.1. The experimental design.

We took advantage of the collaborations between researchers with different skills, the high complementarities between INRA experimental facilities of PTEA (Guadeloupe, semi-open piggery in tropical humid climate) and GENESI (Charentes, conventional closed piggery in temperate climate) and its specific biological pig resources to implement a unique

[11] The INRA research and experimental units are : URZ and PTEA from Guadeloupe; GenPHySe from Toulouse, GABI from Jouy-en-Josas, PEGASE from Rennes and GeNeSi from Poitou-Charentes.
[12] ANR- PigHeaT – project 2012-2016 supported by the National Research Agency : decision ANR-12-ADAP-0015; see the website : http://www.inra.fr/pigheat_eng

combination of studies jointly conducted in tropical and temperate areas (Figure 20). Five Creole boars and 10 Large White sows were used to derive ten F1 boars backcrossed to 65 Large White females in each environment (tropical humid environment and temperate environment). A total of 1,296 half-sib backcross were produced and measured (667 in tropical area and 629 in temperate area). All these animals were genotyped on the 60K SNP chip. High density phenotyping was applied following identical protocols in the two locations. This phenotyping is realized on classic production traits, thermoregulation traits and also new high density phenotypes via transcriptomic and metabolomics techniques on blood and plasma tissues. The choice of backcross design should facilitate the power of detection of chromosome regions involved in heat tolerance, by capitalizing on the divergence between the Large White and the Creole breeds.

5.2. First results.

As previously mentioned, we are currently obtaining the genotypes of BC animals for 60K SNP markers. Hence, the QTLs detection studies are not performed yet, but the first phenotypic results are available.

In our studies in the frame of the PigHeaT project, the backcross growing pigs were produced from the same sires and from highly related dams, and bred similarly in the two contrasted climatic production environments. The tropical piggery was characterized by an average daily ambient temperature of 26.0 ± 0.3°C and an average daily relative humidity of 84.5 ± 0.5%, which correspond to a THI value of 25.0°C (Figure 21). The corresponding values for the piggery in temperate conditions were 25.1 ± 0.6 °C and 61.2 ± 3.8 % for ambient temperature and relative humidity, respectively, which correspond to a THI value of 22.8°C.

The first analyses show differences between sire families due to environmental pressure **[G41]**, with a general reranking of the sires (Figure 22). The average daily gain from 10 weeks of age to 23 weeks of age was 720 g/d (range from 645 g/d to 750 g/d) in the tropical humid conditions and 810 g/d (range from 760 g/d to 860 g/d) in the temperate conditions. The difference between environments was from 50 g/d for the less sensitive family (with an average daily gain of 780 g/d in temperate conditions) to 140 g/d for the most sensitive (with an average daily gain of 850 g/d in temperate conditions). As expected, the average rectal temperature of animals during the growing period was significantly higher in tropical (39.5°C) than in temperate conditions (39.3°C). Similarly to growth rate, differences between sire families were observed for rectal temperature. The difference in rectal temperature between tropical and temperate conditions was from +0.1°C for the less sensitive family (with an average rectal temperature of 39.5°C in temperate conditions) to +0.3°C for the more sensitive family (with an average rectal temperature of 39.3°C in temperate conditions). Based on our first phenotypic analysis, we confirm the antagonism between production traits and heat adaptation. As illustrated by Figure 23, the most robust families for rectal temperature are also the most sensitive families for growth rate. As suggested by Renaudeau et al. (2004) and Dikmen et al. (2012), selection for heat tolerance using thermoregulation traits, such as rectal temperature, will be more benefit by identifying genes affecting thermoregulation traits that do not adversely affect economically important traits.

As a summary, the results of our studies in the PigHeaT project are in the very beginning. The first phenotypic studies showed significant sire family by environment interactions. High GxE interactions may modify the breeding values hierarchy between animals showing different individual sensitivity to heat stress. To our knowledge, only few studies on genetic by environmental temperature (or THI) interactions (GxE) are available (Bloemhof, Mathur et al. 2013). This is mainly due to the lack of accurate genetic relationships between temperate and tropical environments and the lack of large amount of observations. Our future studies will focus on genetic approach to quantify the level of genetic by environment interactions, using classical quantitative genetics approach as well as QTL mapping approaches in order to dissect the genetic architecture of heat robustness and heat sensitivity.

6. Towards the breeding schemes for thermotolerance.

To our knowledge, no practical breeding program including heat tolerance traits in the selection index is being currently conducted. However, it is likely that international private breeding companies are currently taking advantage of the presence of their farms breeding in contrasted areas to select animals dedicated to various environments. In this case, selection is classically conducted with traditional traits of important economic interest (growth rate, body composition, farrowing rate…) and no direct indicators of heat tolerance traits are taken into account in the breeding schemes. Furthermore, the inclusion of heat tolerance traits such as thermoregulation traits, in conventional breeding schemes raises several difficulties. The recorded traits must be biologically relevant and technically easy to record routinely. Moreover, the determination of how much weight thermoregulation traits, such as rectal temperature, should receive in the selection objectives will depend on its economic value and its genetic correlation with other traits. Hence, the economic values must be estimated.

Our studies on simulation of breeding schemes for heat tolerant pigs are in the very beginning **[G40, H9, H11]**. Previous results showed that there is genetic variation of thermoregulation traits, so it makes sense to include thermoregulation traits in a breeding program. However, as mentioned previously, economic values are needed **[E1]**, and it is difficult to determine proper economic values for thermoregulation traits (e.g what is the extra return from a one degree increase in the average upper critical temperature of Large White pig population ?). Because of this key questions difficult to answer (i.e. economic weight), and considering the recent knowledge about the genetic variation of heat tolerance, we used desired gain index to simulate and compare breeding schemes with heat tolerance improvements (in an extreme situation when the general ambient temperature is around 30°C) with conventional breeding schemes (when the general ambient temperature is around 22°C). As mentioned by Rydhmer et al (2010, **[E1]**), the aim of a desired gain index is to select animals so that a predefined desired genetic change is achieved. The economic weights that match the desired genetic gains are then calculated. Figure 24 summarizes our approaches for sire line and dam line, according to our knowledge.

The simulated results should be interpreted with caution for many reasons. For instance, results depend on the values we input for the economic weights and correlations between traits. Economic values of traits are flexible and they highly depend on the situation of the market **[E1]**. Moreover the genetic correlations that are needed for multiple-trait selection including both production and heat tolerance traits are poorly accurate **[A24]**. As pointed out by Knap (2014), due to different constraints (i.e antagonism to neutralize, weaknesses to compensate …), handle breeding program is more or less subjective, more an art than a science. Nevertheless, considering that everything goes the same, our simulations on sire line show that, compared with weights found in a conventional breeding program, greater absolute weights on feed intake and growth rate (1.2 and 0.8 times higher, respectively) were required to obtain similar genetic gain of production traits in heat stress situation than in thermoneutral situation (Figure 25). Concerning the dam-line, we included thermoregulation traits (rectal temperature and respiratory rate). As expected, the simulation shows that the improvement of thermoregulation traits (9% of the total genetic response) was realized with a reduction of production traits (- 57%) but a slight increase in lactation traits (+15 %) and large increase in reproduction traits (+ 136 %) (Figure 26).

As a summary, the evaluation of heat tolerance in breeding programs could be conducted basically through the use of zootechnical performance traits by evaluating pig's breeding values as a function of thermal heat stress or using new phenotypes such as selecting for heat resistance while keeping up the production efficiency. The first method is simpler to implement than the second, but the second method explores both resistance and resilience pathways. Although genetic parameters of thermoregulation traits are produced, further studies are needed. For instance, researches are needed to develop new technologies for automatic recording of thermoregulation measurements in order to accurately estimate individual variation and to estimate accurate correlations with production traits. Sensitivity analysis and economic weights estimations are needed before the implementation of these traits in a breeding index. Nevertheless, thermoregulation traits could be included in a breeding scheme objective but not in the index to check the effect of direct selection on production traits.

Chapter Three: VALORIZATION OF PIG'S ADAPTATION IN NON CONVENTIONAL FARMING SYSTEMS.

1. Introduction.

Pig production systems in the tropics are diverse with a gradient from large specialized structures of industrial farming to backyard pig keepers. In the Caribbean (as well as in Asia, South America and Africa), mixed integrated crop and pig systems have a vast informal background of experiences and traditions with the use of indigenous breed such as Creole pig. This well-adapted breed has traditionally been raised in more rustic ways, using local feeds. However, breed substitution with "exotic" breeds from temperate regions has been widely used. These replacements have proved to be successful in term of production and reproduction performance in tropical industrial pig systems, but with a high dependency on importing expensive raw materials, such as pig feed concentrates. These situations are exacerbated in small islands such in the Caribbean for which local feed resources from crops with high content of digestible protein for pig are limited **[B2]**. Due to their high protein and energy requirements (e.g. 12.2 MJ/d for maintenance requirements in Large White growing pigs, Renaudeau et al., (2006)) and also to their high sensitivity to heat, the pig breeds specialized for productive purpose could not be suited to the majority of traditional low-input production systems. At the opposite, due to their low requirements and rusticity (e.g. 9.6 MJ/d for maintenance requirements), Creole pigs are able to better valorize local feed resources. Furthermore, the Creole breed deserves to be maintained for at least three reasons: i) economic interest: by developing a niche market that valorize the high organoleptic and technological qualities of the meat (Depres et al., 1994; Renaudeau et al., 2005; Xande et al. 2009); ii) biodiversity considerations to preserve between-breed genetic diversity and maintain and secure valuable alleles for the future **[E1]**; iii) scientific considerations: because Creole pig is an original biological model to understand physiological and genetic mechanisms underlying heat tolerance (see Section 3 and 5 of Chapter 2). A SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis for breeding schemes for the Creole pig population is described in Table 6. As mentioned by Rydhmer et al (2010, **[E1]**), such an analysis could be a good starting point for a discussion involving all stakeholders.

Our studies on the valorization of adaptation of pig to tropical farming systems are part of a larger research topic. The aim is the understanding of the complex nature of mixed farming systems **[A18]**. The global objectives are to better characterize the integration between crop and livestock and to propose innovative systems that optimize nutrient cycling and use of local resources within an agroecological framework. Our scientific approach adopted for pig is summarized in Figure 27 (Dedieu et al., 2011). We both use forward and backward approaches. Carrying out the work require some investigations to characterize mixed farming systems or backyard rearing, conceptual and systemic modelling, and system and targeted experiments. These studies were mainly focused on the valorization of INRA-URZ results on the characterization of nutritional values of tropical feed resources [**A10**, **A13**, **B2**, **C4**, **C5**, **D1**], (Xandé, Regnier et al. 2010)] and on the characterization of the local Creole breed (see Section 3 of Chapter 2).

2. Characterization of non-conventional pig farming systems.

Surveys in Guadeloupe have shown that Creole pig farms differ from each other mainly by the number of sows and the feeding system **[B1, H10]**. These farmers rely on their own labour and on the resources of their farms, and their network of contacts for the renewal of animals (piglets, boars) and for marketing.

Our studies show that there are three types of Creole pig production systems. They are differentiated according to the population size, the age of the farmer, the livestock management and the proportion of crossbred pigs. Those pig systems are included in mixed farming systems.

The observed growth performance is lower than those obtained in specialized systems. Based on the survey data, the average daily gain between weaning and slaughter is approximately between 150 and 300 g/d. Corresponding values in specialized systems are in the range of 400 to 700 g/d. These differences between production systems are mainly related to different production logic and objectives. One is to produce meat and manure with limited use of inputs, through an overall optimization of the farming system, for which the pig system is only a component. The specialized system is designed to maximize animal performance. The survey also shows that the preservation of the Creole pig breed becomes a concern, given the large number of crossbred animals.

3. Genetic management of small population.

In Guadeloupe, the Creole pig breed was composed of approximately 1,200 sows (Rinaldo et al., 2003). The data collected from our non-exhaustive surveys in 2009 **[H3]** and 2014 **[H9]** suggest that the number is declining. Thanks to the contribution of the breed association SOSPIG and the Creole pig network derived from surveys, we have collected blood samples for DNA extraction and we were able to assess the genetic diversity of the population via microsatellites **[G27]**.

From the analysis of genetic distances between Creole pigs, five groups have been drawn (Figure 28). This classification based on molecular markers was similar to the geographic clustering of farms. About 46% of the genetic diversity of the Creole population analyzed is from the Marie-Galante island. This is in relation to highest population size in the island than elsewhere in the archipelago of Guadeloupe. The number of pigs reduces the risk of genetic drift. This analysis of genetic diversity has allowed us to constitute the Creole sires (F0) for the experimental design for QTLs detection (see Section 5 of Chapter 2). Indeed, the

implementation of F0 populations had required the choice of the most genetically distant animals.
Furthermore, I had the opportunity to realize one-year post-doctoral position in 2008-2009, under the direction of Pr Lotta Rydhmer, in Division for Pig Breeding of the Department of Animal Breeding and Genetics of the Swedish University of Agricultural Sciences (SLU) in Sweden. I got involved in the EU-Q-PorkChains project within Module II - Diversity, flexibility and sustainability on farm-level production systems **[E1, A22]**. In this framework, I realized two simulation studies on breeding programs **[A11, A16]**. Even if not performed in a tropical context, the results of the second simulation study dealing with the management of selection and inbreeding in small local pig breed **[A16]** can be a reference for genetic management in the tropics. Indeed, the results showed that there is room for some selection also in a small population (300 sows), like the Creole local breed population. With optimum contribution selection, a genetic progress almost as large as with Best Linear Unbiased Predictor (BLUP) evaluation can be achieved (between 0.2 and 0.5 genetic standard deviation) with a rate of inbreeding that is much lower than with BLUP evaluation (from 0.7 to 1.2 % vs 2.3 to 5.7 % in BLUP).

4. Towards the conception and evaluation of innovative pig production systems.

We are at the beginning of system and targeted experiments aiming at validating the different scenarios established from systemic modelling of pig rearing **[C3, G23, G37]**. Our first results are in the framework of the evaluation of the optimal conditions for the implementation of low input pig production systems. The first studies aimed at characterizing feeding behavior and activities, and growth rate and thermoregulatory response of growing pigs, raised in an outdoor system with a sweet potato field supplemented with soybean meal. Even if they are preliminary results **[G33, G39]**, these studies show that in the framework of mixed farming systems, pigs can provide ecological services. For instance, pigs can valorize a sweet potato field or any crop residuals that cannot be commercialized (but still edible) due to damage by weevils or nematodes, and thus they can reduce the use of herbicides and tillage before planting the next following crop (Photos 1).

Chapter Four: GENERAL CONCLUSIONS AND FUTURE PERSPECTIVES

As a conclusion from the work that I have performed for 12 years at the INRA-URZ, I would like to lay stress on the human and scientific richness of the URZ multidisciplinary team. And I would like to thank the financial, technical and scientific support from the Animal Genetics Department. The main work I have made in this manuscript was to highlight the results obtained collectively with students, PTEA technicians, PhD students, researchers from URZ and administrative colleagues. Furthermore, a part of this work is from a strong collaboration with other research and experimental units from INRA (e.g. GenPHySE from Toulouse, PEGASE from Rennes, GeNeSi from Magneraud) and international collaboration (SLU, Sweden; Aarhus, Denmark).

During these years, I dealt with three main topics: characterizing genetic variability of heat tolerance in pig; conceiving and implementing an experimental design for identifying and mapping QTLs related to heat tolerance; conceiving and evaluating non-conventional pig farming systems. My work is an illustration of how genetic studies can contribute in the development of the scientific project of the multidisciplinary URZ team. This allowed me to develop a global approach on issues of genetic adaptation of pigs to heat. The URZ is like an organism in which each cell puts its capabilities at the service of the whole.
I have acquired project management skills. I have the privilege to animate the network formed by the PigHeaT project, with the support of colleagues of GenPhySe from Toulouse and of PEGASE from Rennes. This new management implies better organizing my ongoing and future main activities, including i) the ongoing and future works on identifying genes for heat tolerance; ii) the future works on the genetic variability in resources allocation in pigs, with its interactions with heat tolerance; iii) the future works on including heat tolerance in breeding schemes; iv) the ongoing and future works on farming systems; v) my activities annexes such as university teaching; vi) and finally my expertise in statistics and management of local pig breeds. The prospects that I describe in this chapter are part of the time step of the new unit project 2014-2017: "Promote in an Agro Ecological Perspective, efficient breeding systems in strong environmental constraints".

1. Identify genes for heat tolerance.

The 2010-2014 periods was particularly marked by widespread tool use "omics". It took me adaptation (and I still need) to the analysis of data generated by these new technologies, where "classic" quantitative genetics has become almost obsolete, especially in the context of complex traits such as heat tolerance traits. In the framework of the PigHeaT project and the thesis of R. Rosé (2014-2017), the objective is to identify the genomic regions involved in heat tolerance. The genome-wide association study (GWAS) analyses will be performed using i) the genotyping information collected on 1,120 siblings issued from Large White and Creole pig backcross and genotyped on the 60K SNP chip; and ii) the performances and thermoregulatory responses of these animals recorded in tropical and temperate environment. The main objectives of the QTLs detection are to identify QTLs robust to heat stress.

2. Characterize genetic variability in resources allocation in interaction with heat tolerance.

As previously mentioned, during chronic heat stress conditions, reduction in voluntary feed intake is observed in pigs with negative consequences on performance in pigs and sows. This reduction in appetite may induce trade-off in the partitioning of nutrients and metabolism of pig between maintenance (survival and longevity) and (re)production. Understanding the genetic control of the nutrient resources allocation in interaction with heat stress may highlight relevant biomarkers for selecting heat tolerant animals. This future study will be performed by the expected new recruit at the URZ team (end of 2015), and I will be in strong interaction with my new colleague. This profile represents an evolution in our works on adaptation to heat, by considering wider environmental constraints (heat stress, sanitary and feed) and by positioning in terms of regulating nutrients allocation.

3. Integrate heat tolerance in breeding schemes

In the context of sustainable pig production systems, the breeding objective aims at better balance between production and functional traits. Heat resistance should then be increased to improve heat tolerance, without compromising the high production level of pigs. Integrate heat tolerance in breeding schemes is the practical output of our genetic studies. It relates on results produced in our previous studies and our future findings on biomarkers that are likely to be good predictors of heat tolerance. Depending on the future results on QTL mapping, strategies for genetically improving heat tolerance of pig will be investigated by defining the way heat tolerance should be included in the breeding objective, investigating the interest of phenotypic and genomic information as selection criteria.

4. Characterize viability of mixed farming systems.

I will continue to deal with the evaluation of mixed farming systems by focusing on innovative pigs systems. Given my responsibility in my main topic on genetic of heat adaptation, particularly through the ongoing PigHeaT project (scientific coordination, identifying QTLs, thesis supervision …), I will invest to a lesser extent in the conception and evaluation of pig production systems. Nevertheless, I want to keep this mission because it is complementary to the genetic approach and it allows me to have a more holistic approach (incorporating our findings on the genetics, nutrition and physiology) and a direct link with the local stakeholders. One of our main desired outcomes is to propose finalized solutions for the development of a sustainable niche market oriented to the valorization of the Creole pig breed (from the genetic management to the final high meat quality products).

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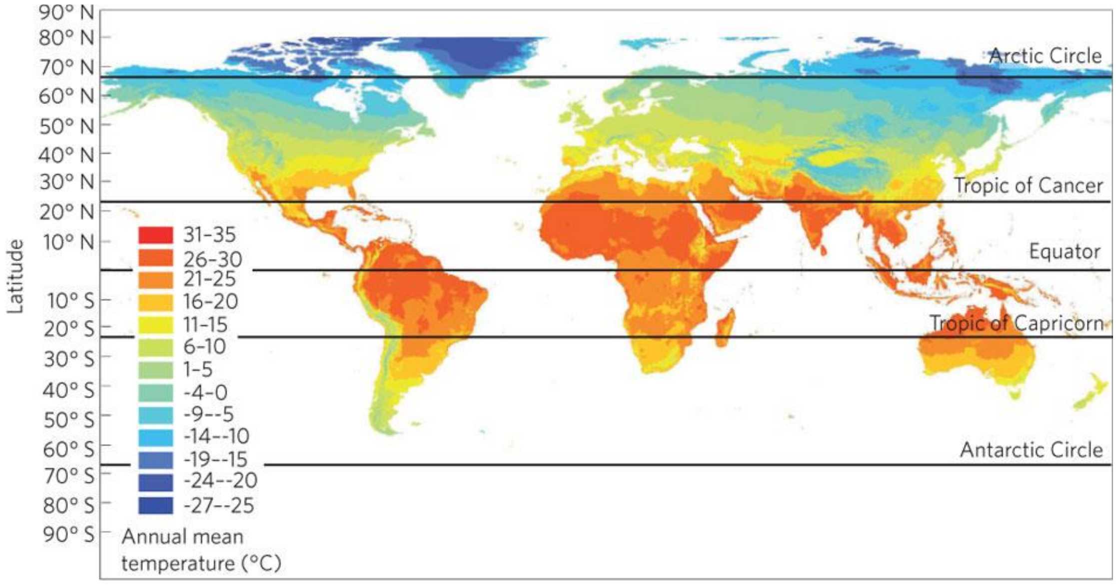
FIGURES

Figure 1. World climate map (from Saikkonen et al., 2012)



.**Figure 2**. World map of pig production (average values from 2000 to 2013); source: FAOSTAT: http://faostat3.fao.org)

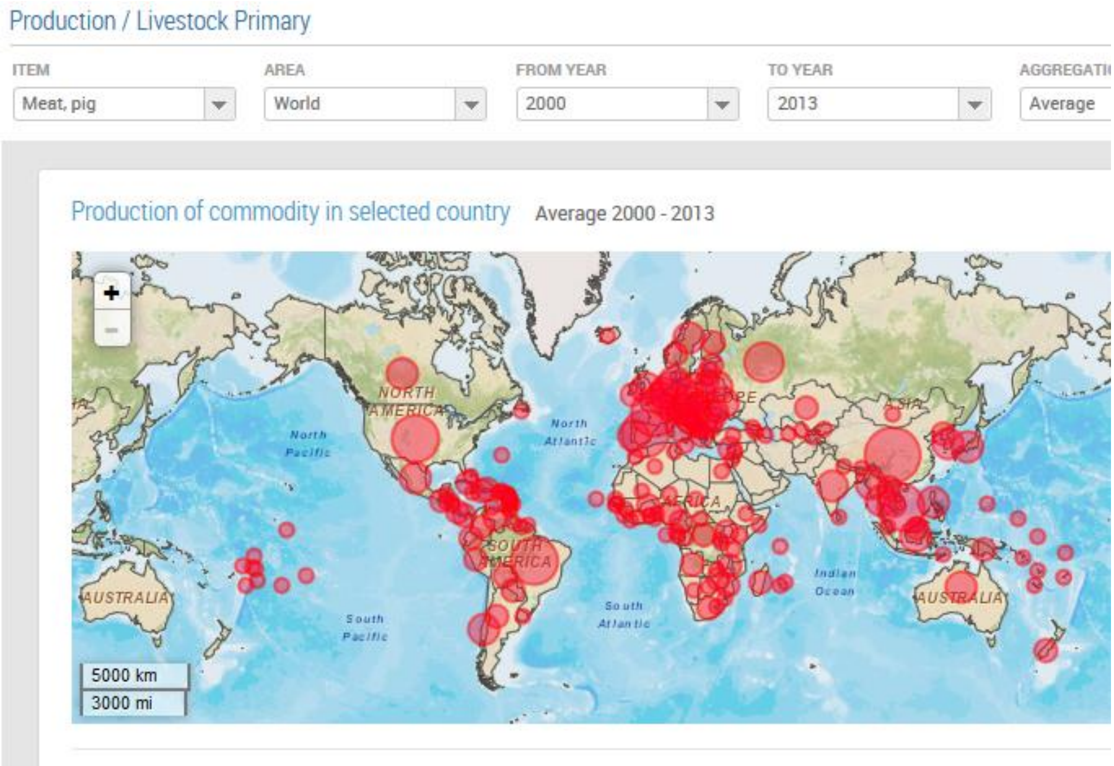


Figure 3. Structure of the URZ's project including and researchers' name and skills.

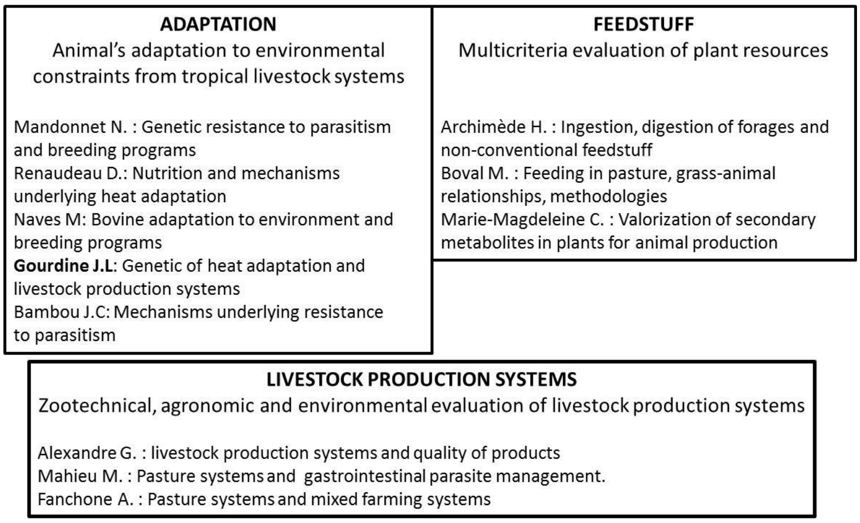


Figure 4. Representation of my research activities (realized and going on) and the list of Master students that I have supervised. Legend: In blue, my activities for genetic variability of heat adaptation; in green my activities for valorization of pig's adaptation in farming systems.

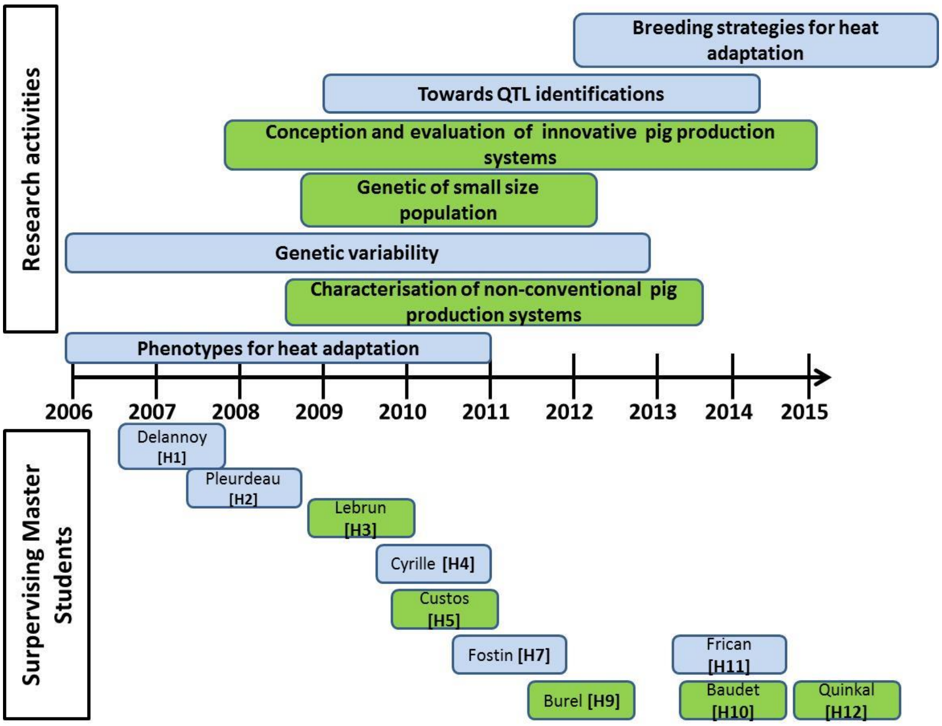


Figure 5. Diagrammatic presentation of the effect of ambient temperature on lactating sow (indicative values in blue) or growing pig (indicative values in green) metabolism and body temperature (adapted from **[C8]**). The lower critical temperature is the ambient temperature below which pig must increase heat production to maintain heat balance. The upper critical temperature is the ambient temperature above which pig must increase heat loss rate to achieve heat balance.

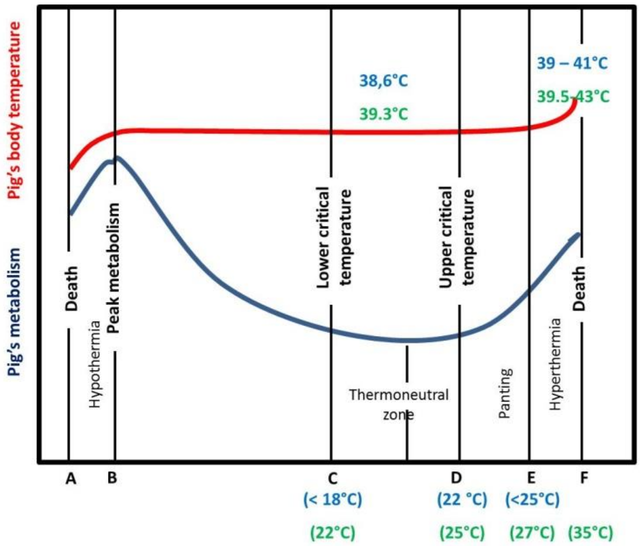
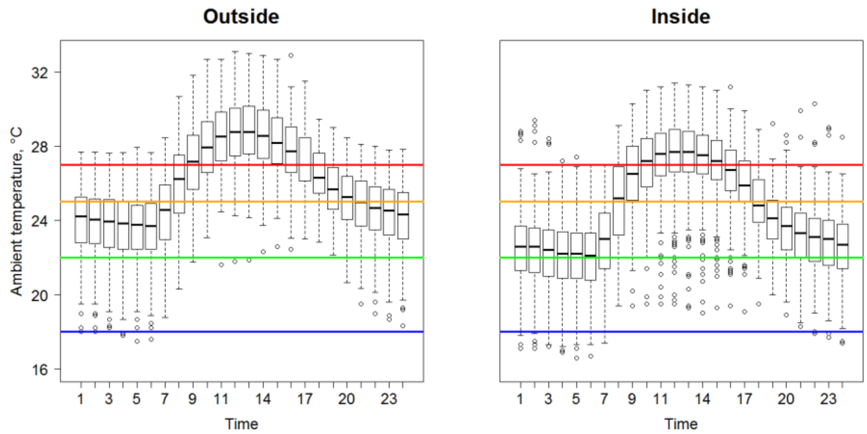


Figure 6. Daily fluctuations of ambient temperature (a) and relative humidity (b) from outside and inside of the experimental farm. The values correspond to mean hourly ambient temperature between November 2010 and May 2014 for which outside and inside climatic parameters are available. Blue lines: 18°C or 50%; green lines: 22°C or 70%; yellow lines: 25°C or 80%; red lines : 27°C or 90%.

(a)



(b)

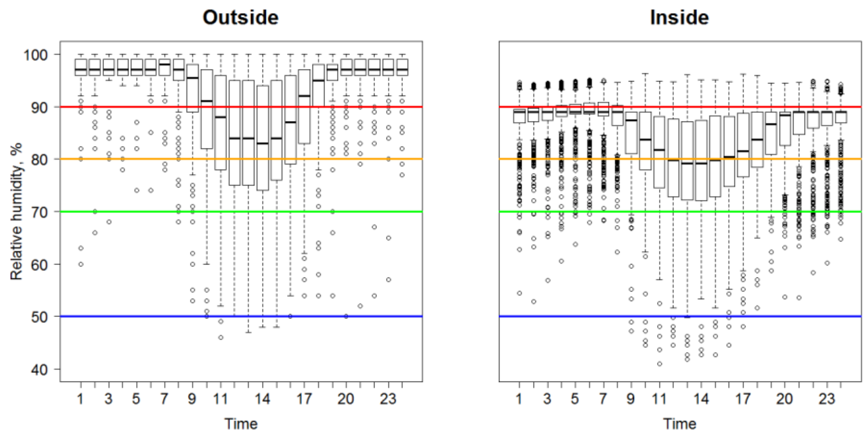


Figure 7. Measurements realized in lactating sows (adapted from **[A24]**)

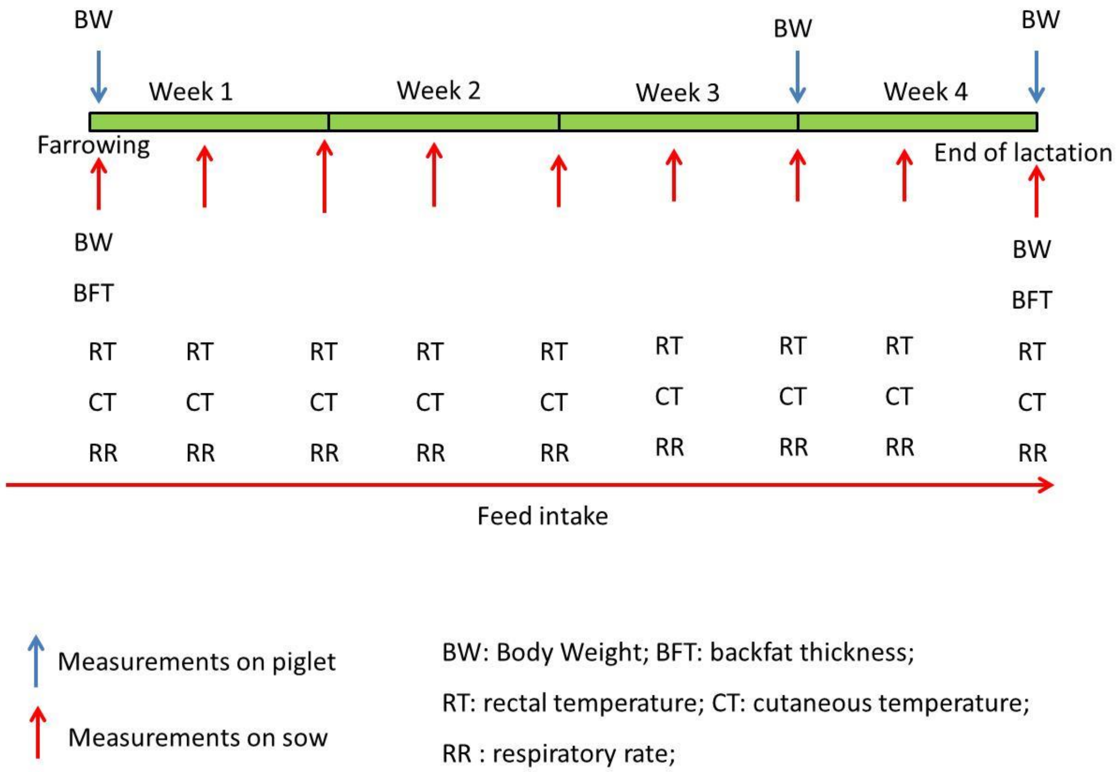


Figure 8. Hourly time-course of rectal temperature (a) and feed intake (b) in lactating sows and ambient temperature during mid-lactation (d14-d15). Each rectal temperature point is the least squares mean of a total of 32 lactating sows. Each feed intake point is the least squares mean of average of a total of 26 lactating sows (adapted from **[H1 and A5]**).

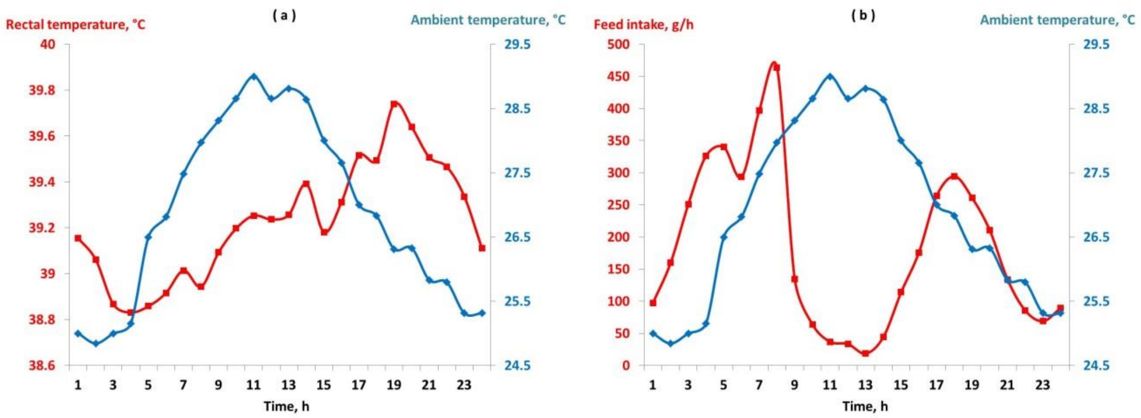


Figure 9. Daily time-course of rectal temperature and average daily feed intake in lactating sows from during lactation (from d0-d28). Each rectal temperature point is the least squares mean of a total of 109 lactating sows and each feed intake point is the least squares mean of 179 lactating sows (adapted from **[A4 and A6]**).

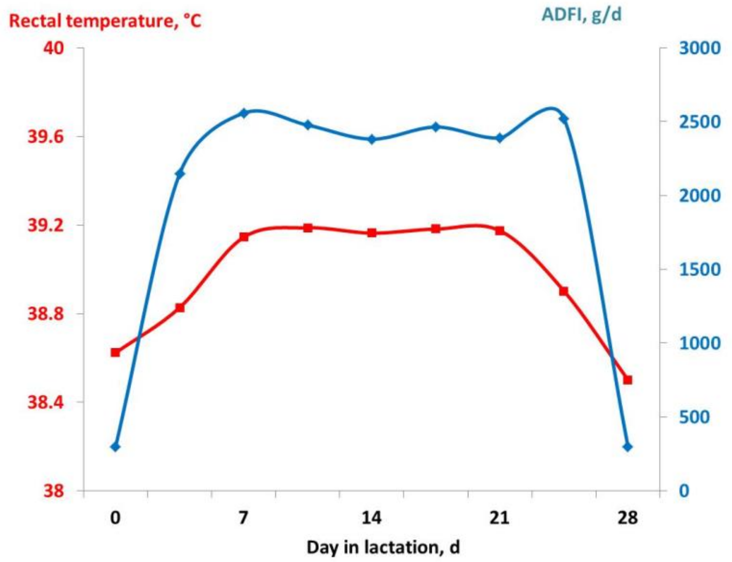


Figure 10. Effect of the average THI during lactation on the average feed intake (a), the litter BW gain (b) and sow's BW loss (c) (adapted from **[A24]**).

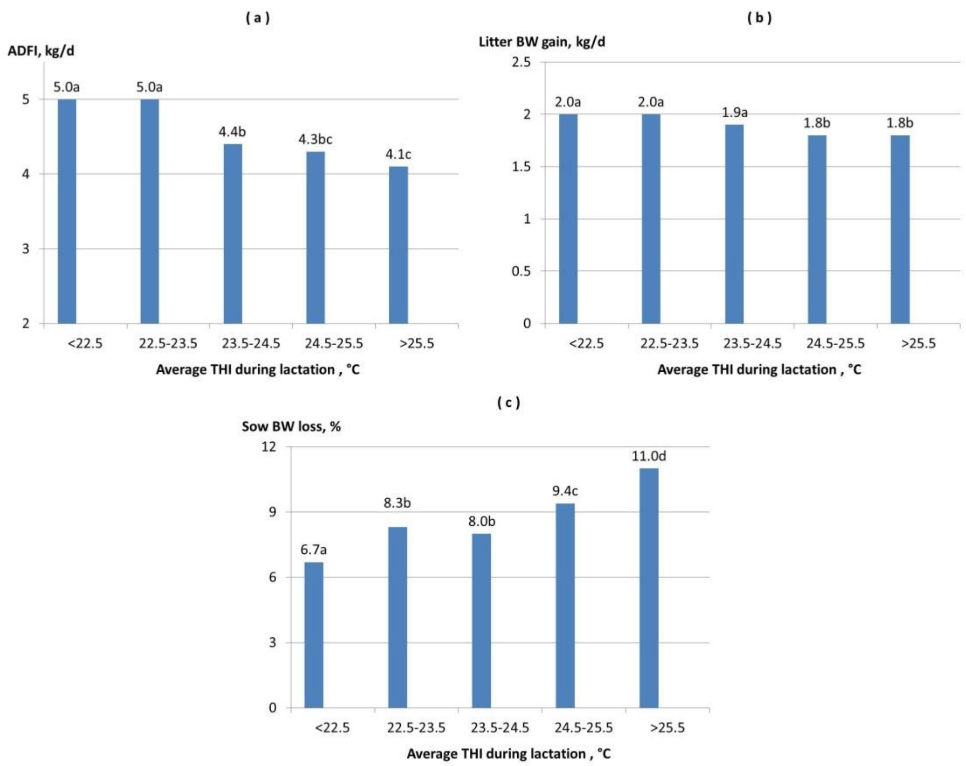


Figure 11. Effect of the average THI during lactation on the average thermoregulatory responses of lactating sows. (adapted from **[A24]**).

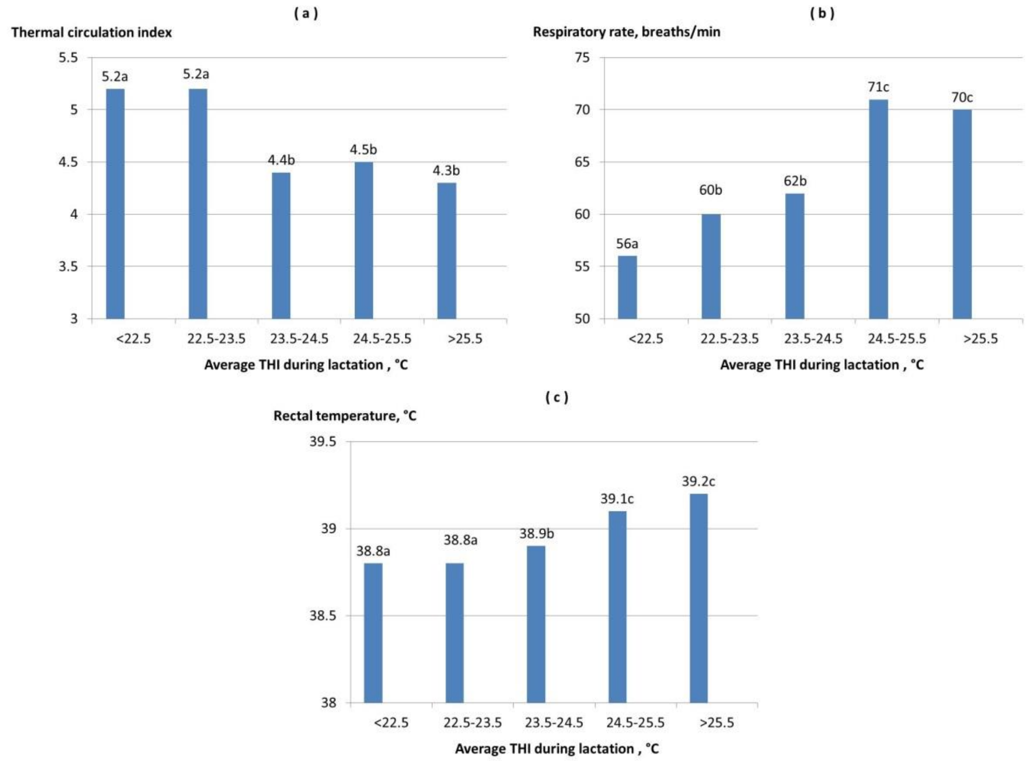


Figure 12. Effect of the average THI during lactation on the deviation of thermal circulation index (a) and rectal temperature (b) of lactating sows at 07:00 h and at 12:00 h. (adapted from **[A24]**).

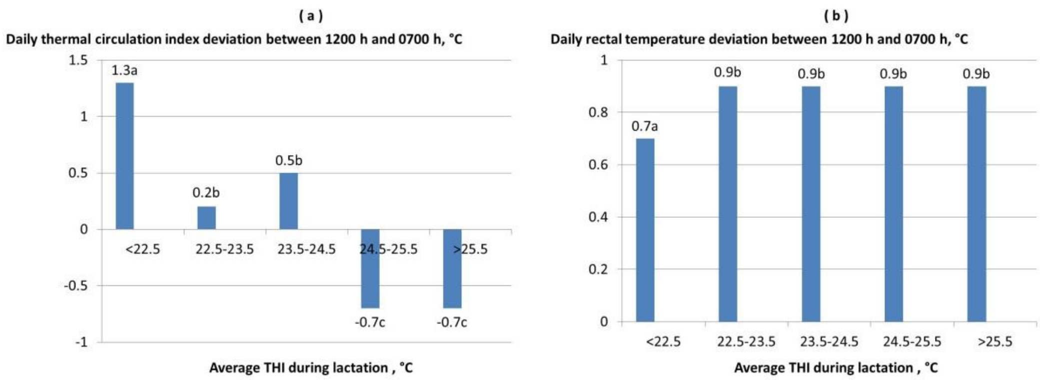


Figure 13. Example of the variation of backfat thickness at farrowing taken from a population of Creole sows and Large White sows of which feed allowance was calculated to standardize body condition at farrowing (adapted from **[A4]**).

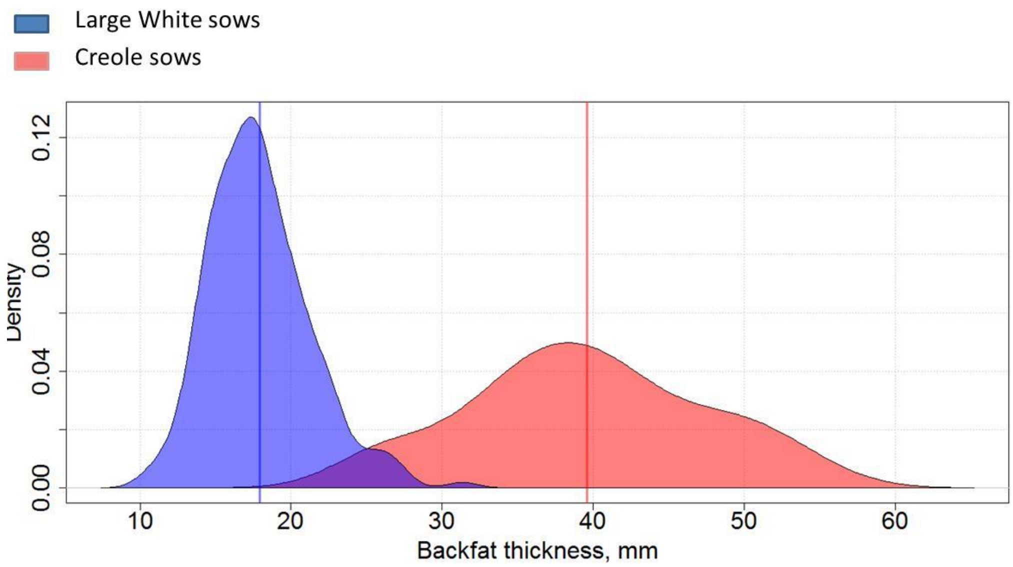


Figure 14. List of functional and production traits studied in INRA-URZ in experiments aiming at comparing the effect of heat stress on Large White and Creole breed.

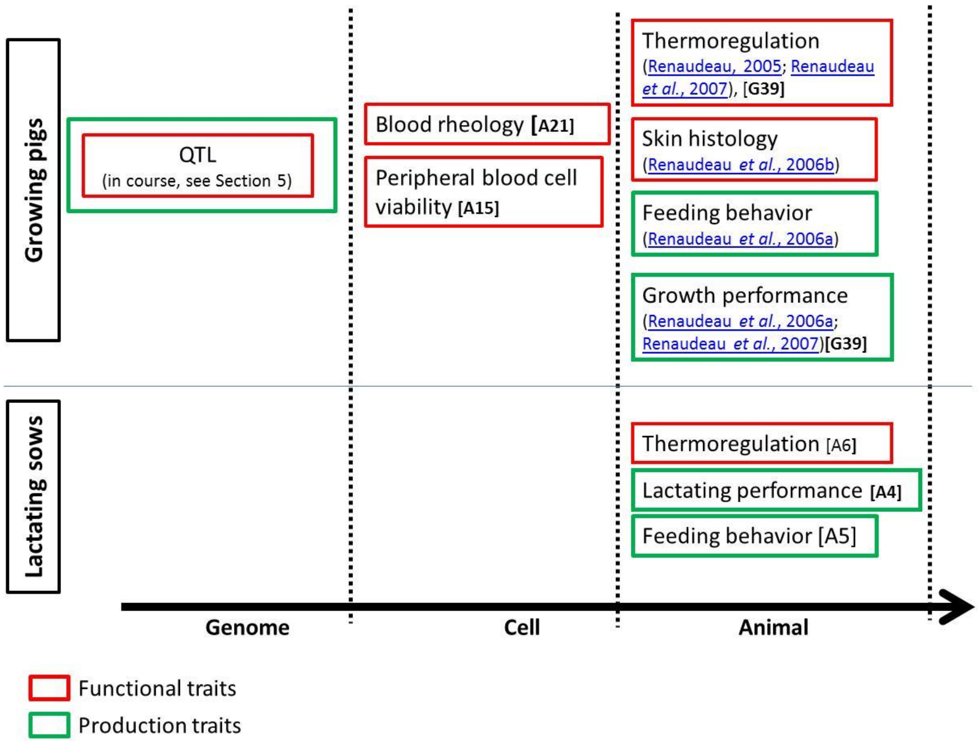


Figure 15. Density distribution of rectal temperature of Creole and Large White lactating sows according to the average THI during lactation. (adapted from **[A6]**).

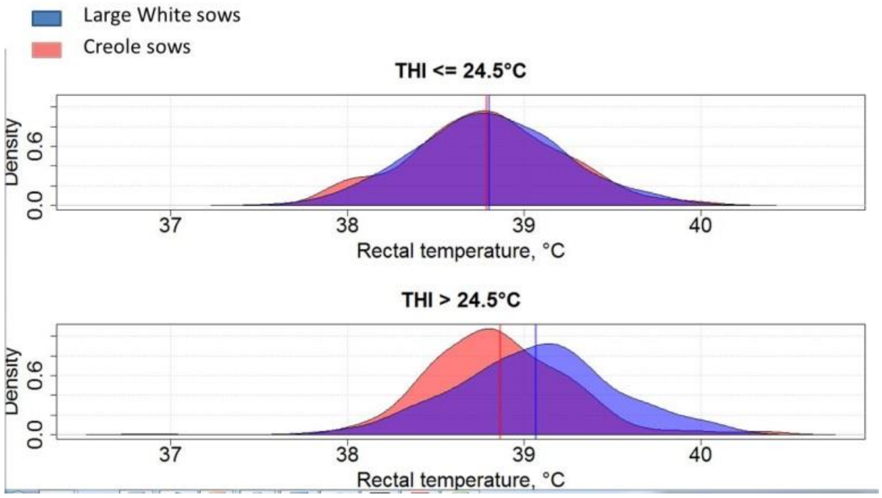


Figure 16. Density distribution of skin temperature of Creole and Large White lactating sows according to the average THI during lactation. (unpublished results).

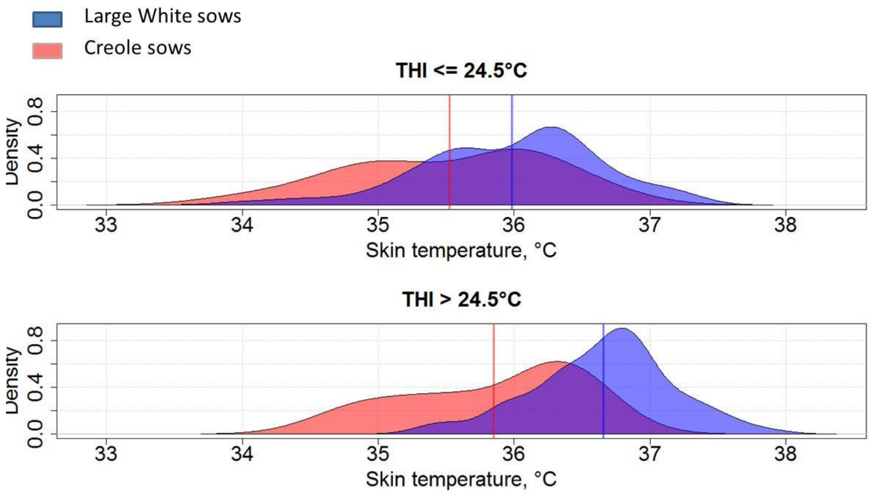


Figure 17. Density distribution of respiratory rate of Creole and Large White lactating sows according to the average THI during lactation. (unpublished results).

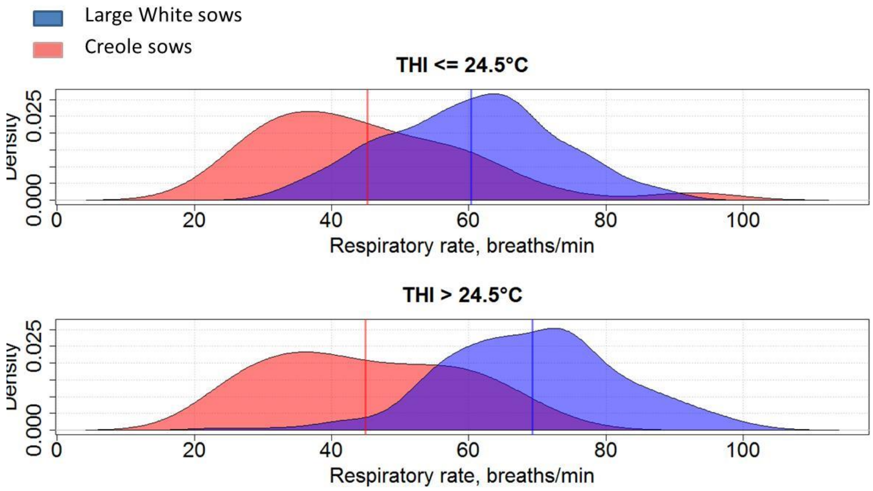


Figure 18. Heritability (h²) for rectal temperature (RT), cutaneous temperature (CT), respiratory rate (RR) at 07:00 h and at 12: 00 h and daily feed intake (DFI) as a function of period of lactation. The heritabilities were estimated using random regression models using ASReml software (Gilmour et al., 2009; adapted from [A24]).

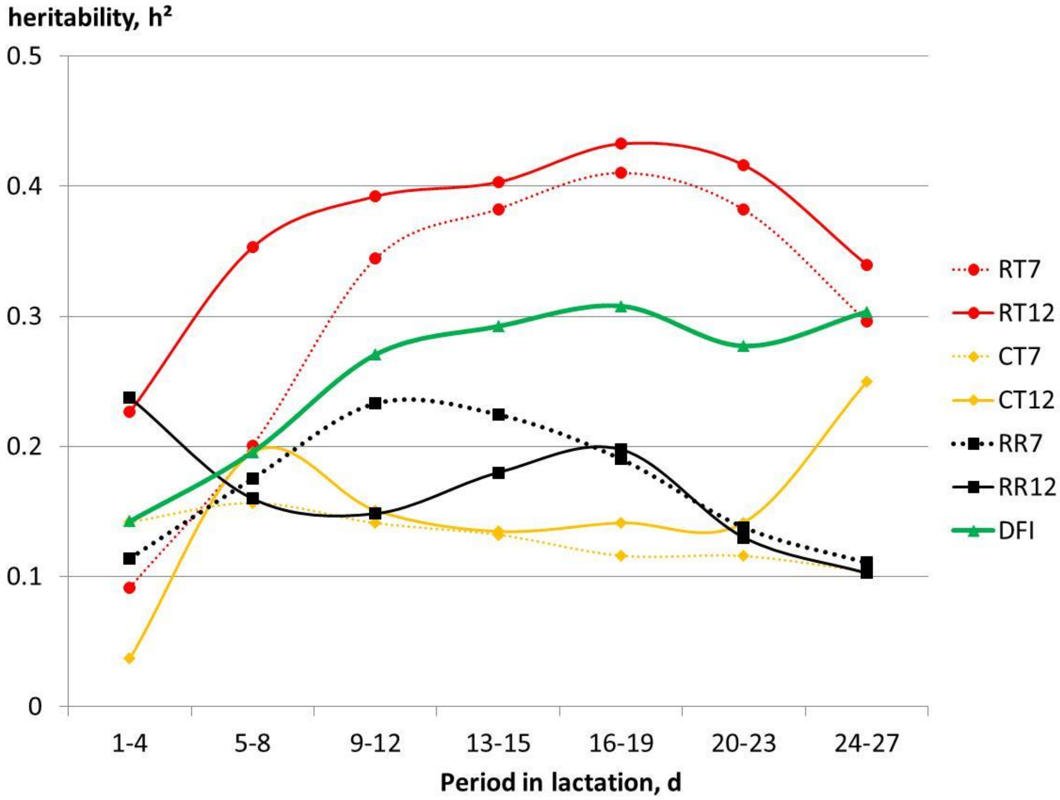


Figure 19. Variance components of rectal temperature during lactation depending on the period in lactation. The variance components were estimated using random regression models using ASReml software (Gilmour et al., 2009; adapted from [A24]).

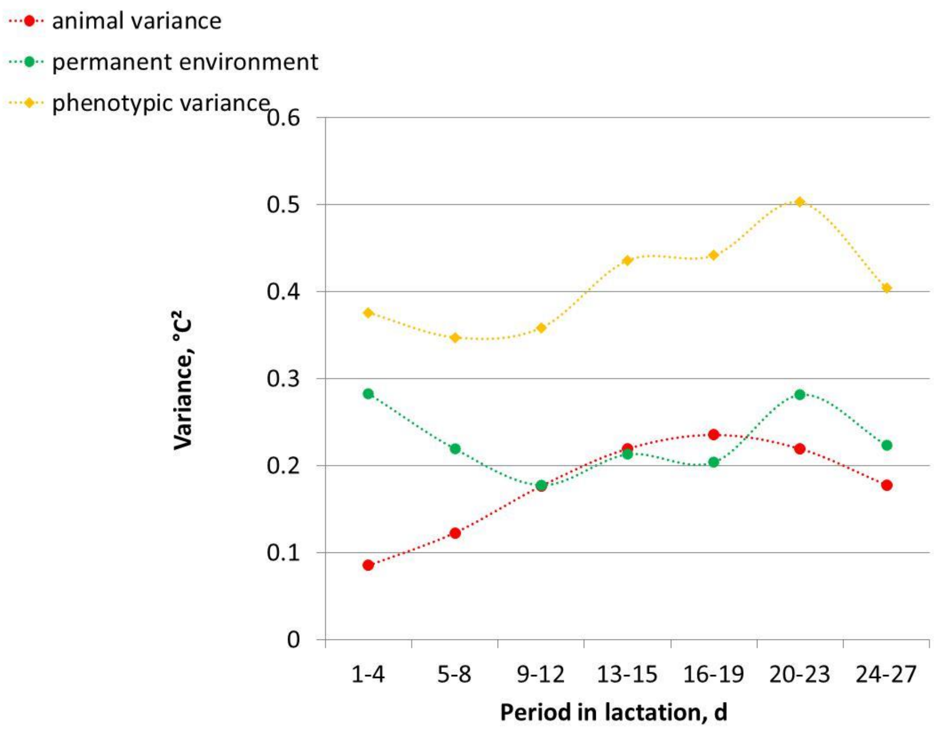
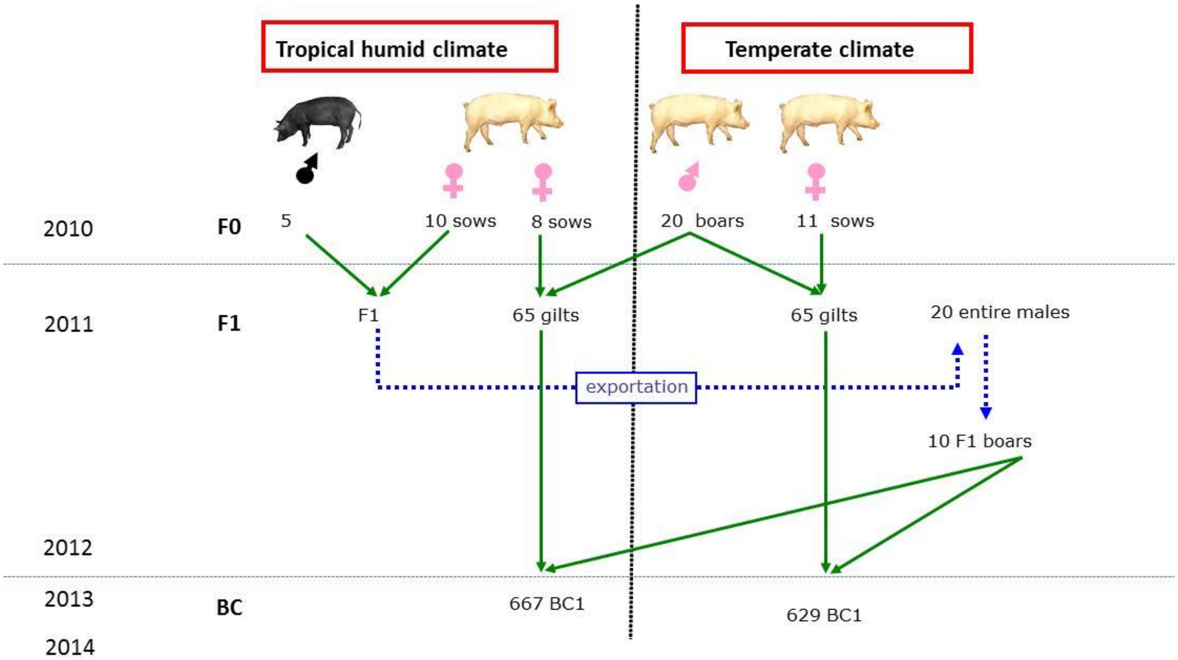


Figure 20. Experimental design for production of backcross pigs in tropical and temperate INRA experimental units.



Macro-phenotypes: feed intake, feed efficiency, feeding behavior, growth rate, body composition, body temperatures, morphological characteristics

Figure 21. Monthly variation in the indoor temperature-humidity index (THI) in the two experimental farms in tropical humid conditions (INRA-PTEA, Guadeloupe; semi-open piggery) and temperate conditions (INRA-GenNeSi, Charentes, closed piggery). Each value corresponds to the daily indoor THI between March 2013 (the beginning of the measurements on backcross growing pigs) and October 2014 (the end of the measurements). Blue lines: 22°C; green lines: 24°C; yellow lines: 26°C ; red lines : 27°C ([adapted from **[G41]**).

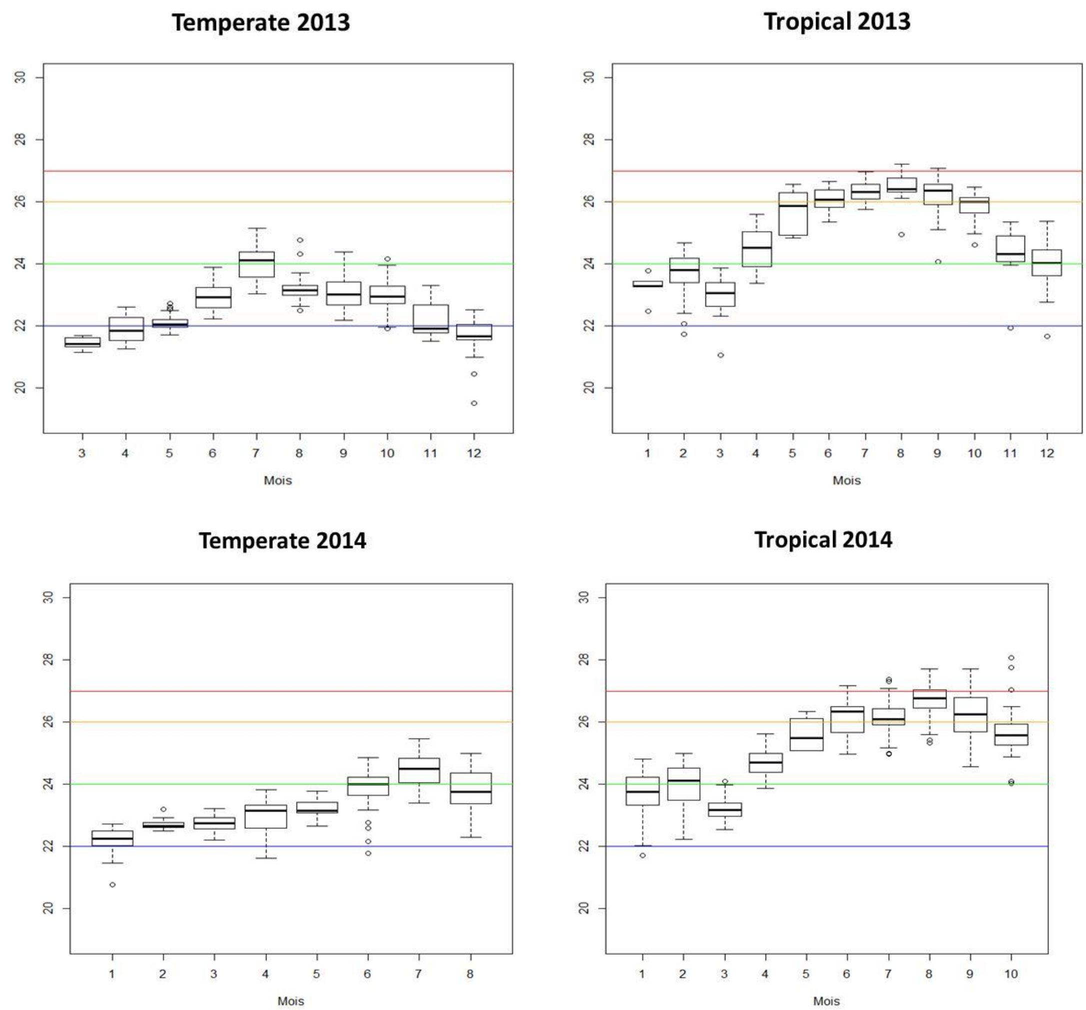


Figure 22. Least square means values of average daily gain (a) and rectal temperature (b) of backcross growing pig according to the sire's origin. ([adapted from **[G41]**).

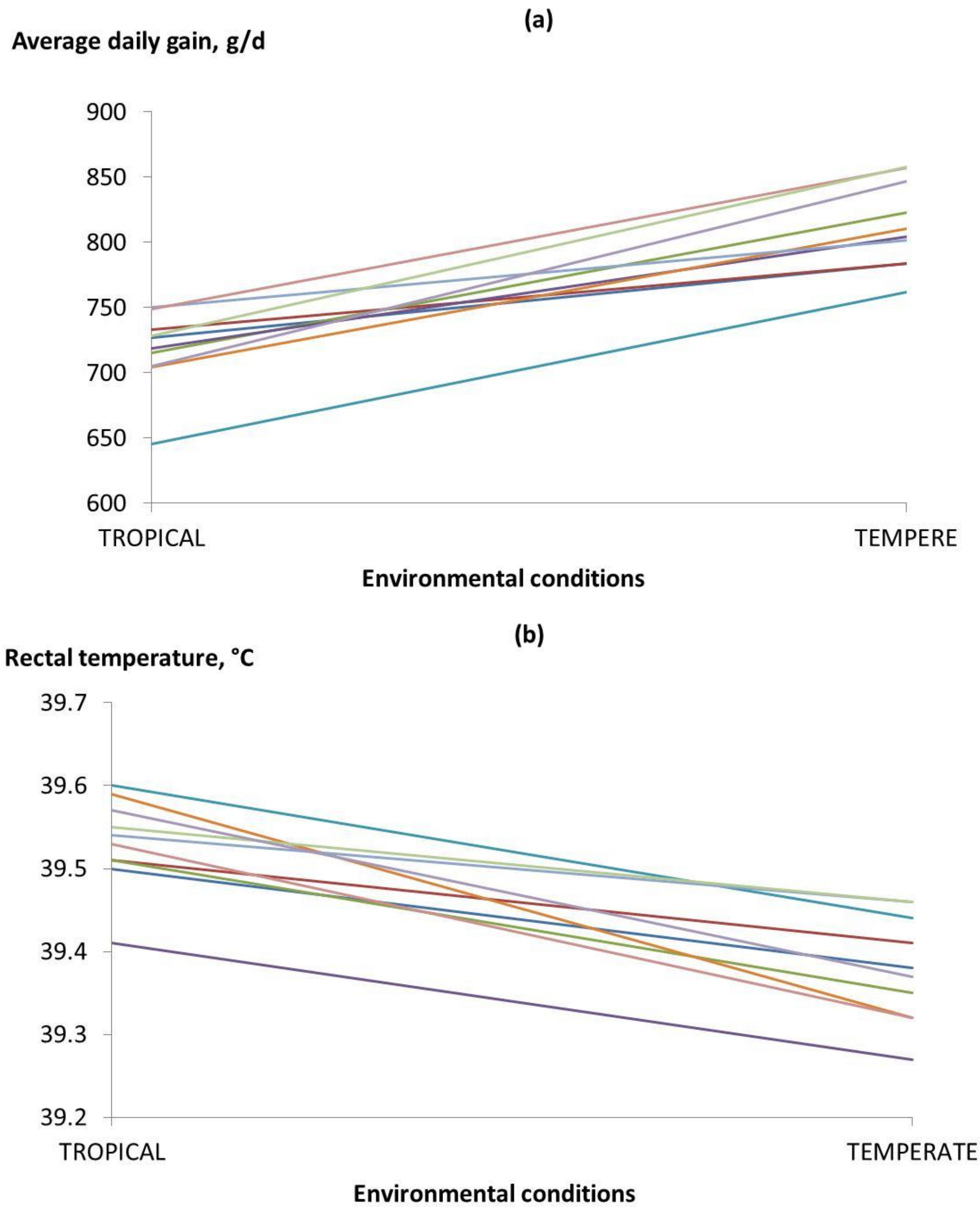


Figure 23. Hierarchy of sire families according to the average differences of the rectal temperature and growth rate between temperate and tropical conditions of backcross growing pigs during growing period. ([adapted from **[G41]**).

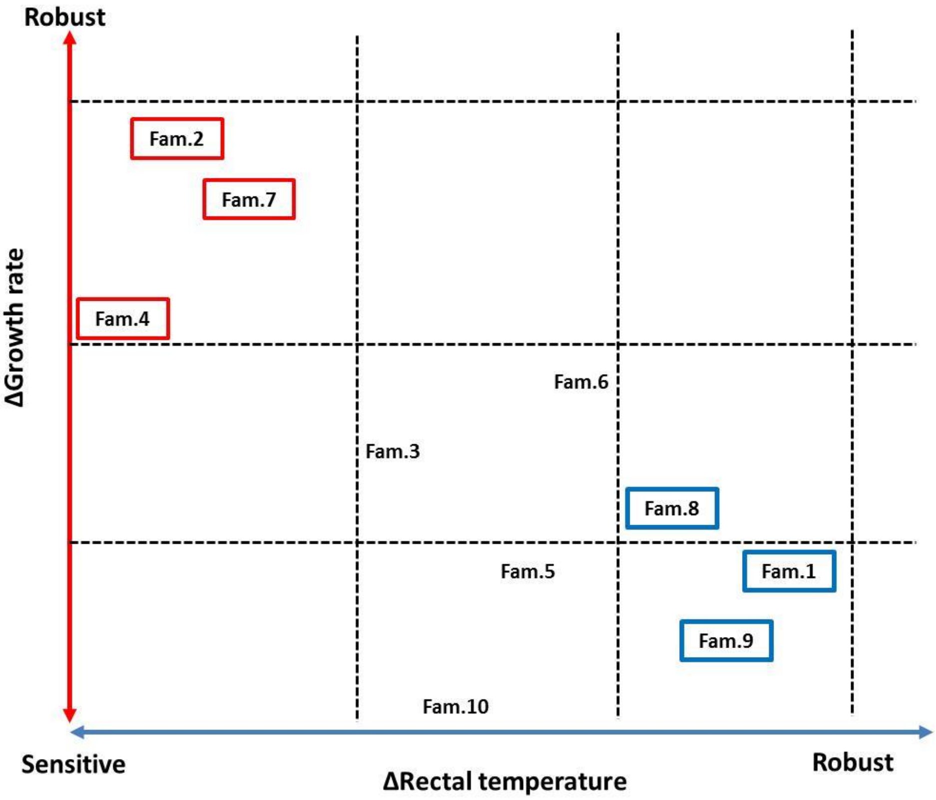


Figure 24. Description of the general approaches used in the simulation studies (in sire line and in dam line) comparing conventional schemes to a breeding scheme.

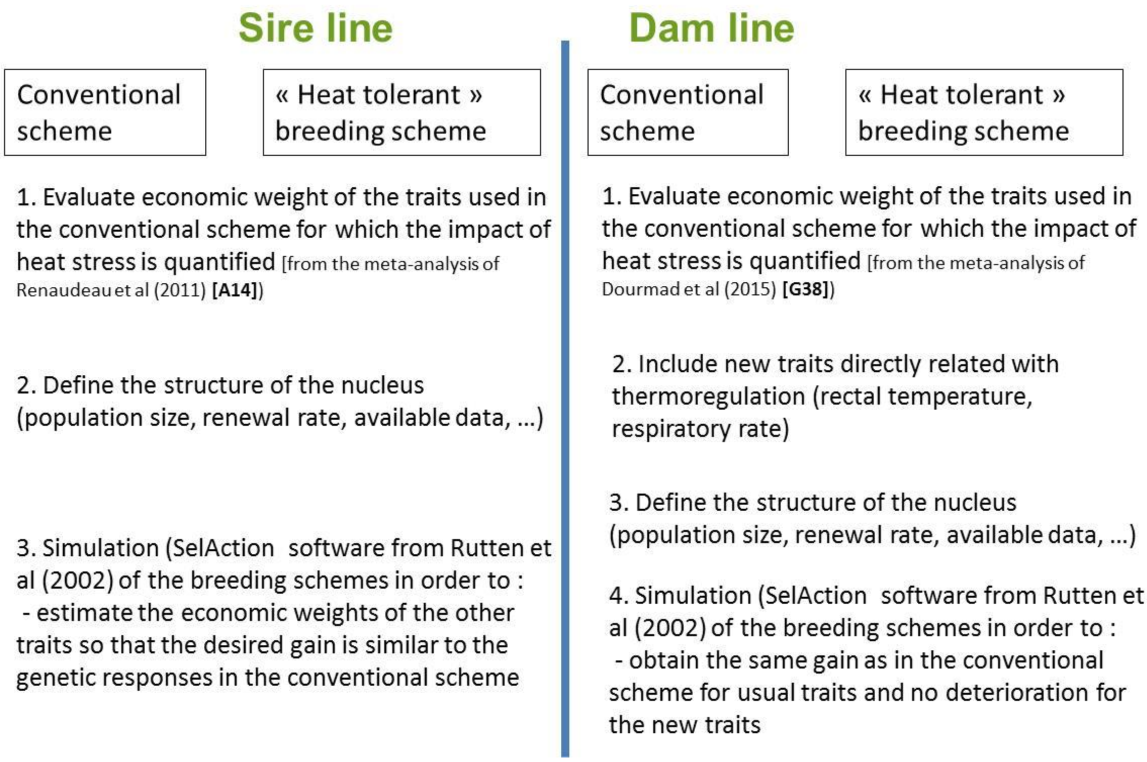


Figure 25. Relative differences between economic weights for heat tolerant breeding scheme and conventional economic weights in a sire line (adapted from **[H9]**). The relative difference was calculated with the following formulae :as $(EV_{HT} - EV_c)/EV_c$ where EV is the economic weight, c is for conventional and HT for heat tolerance.

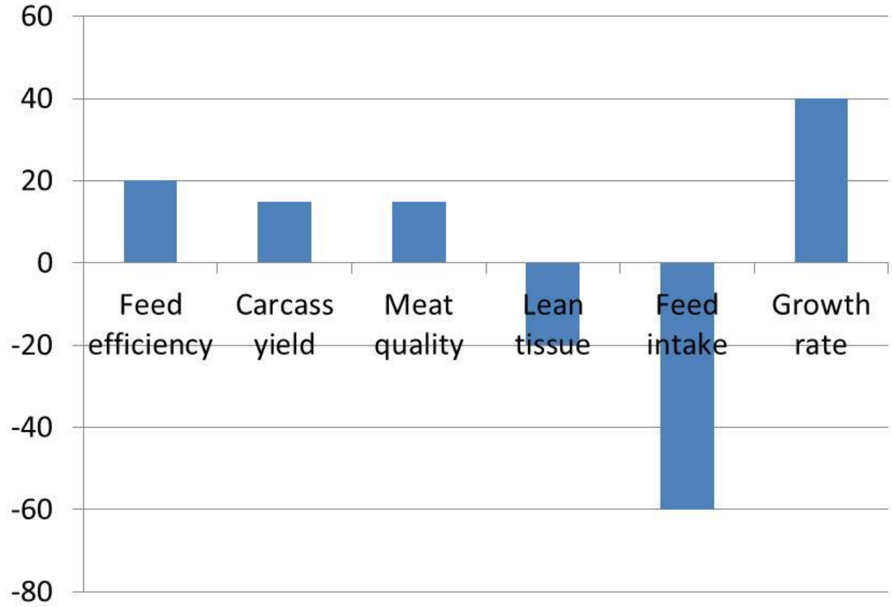


Figure 26. Assumed relative weight (a) and annual genetic gain (b) in simulated dam-line breeding schemes including thermal tolerance traits (2) compared with conventional breeding schemes (1) (adapted from **[G40]**).

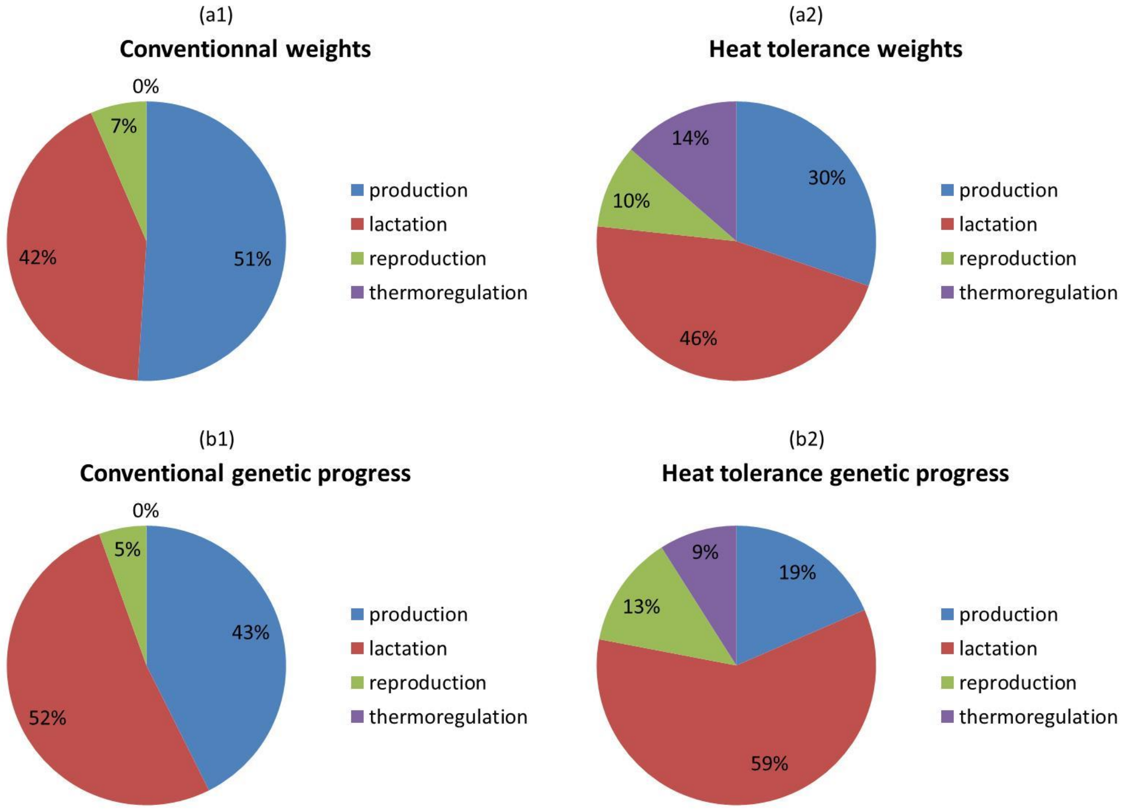


Figure 27. Our scientific approach for the conception and evaluation of alternative pig farming systems within the framework of mixed framing systems research (adapted from (Dedieu et al., 2011)).

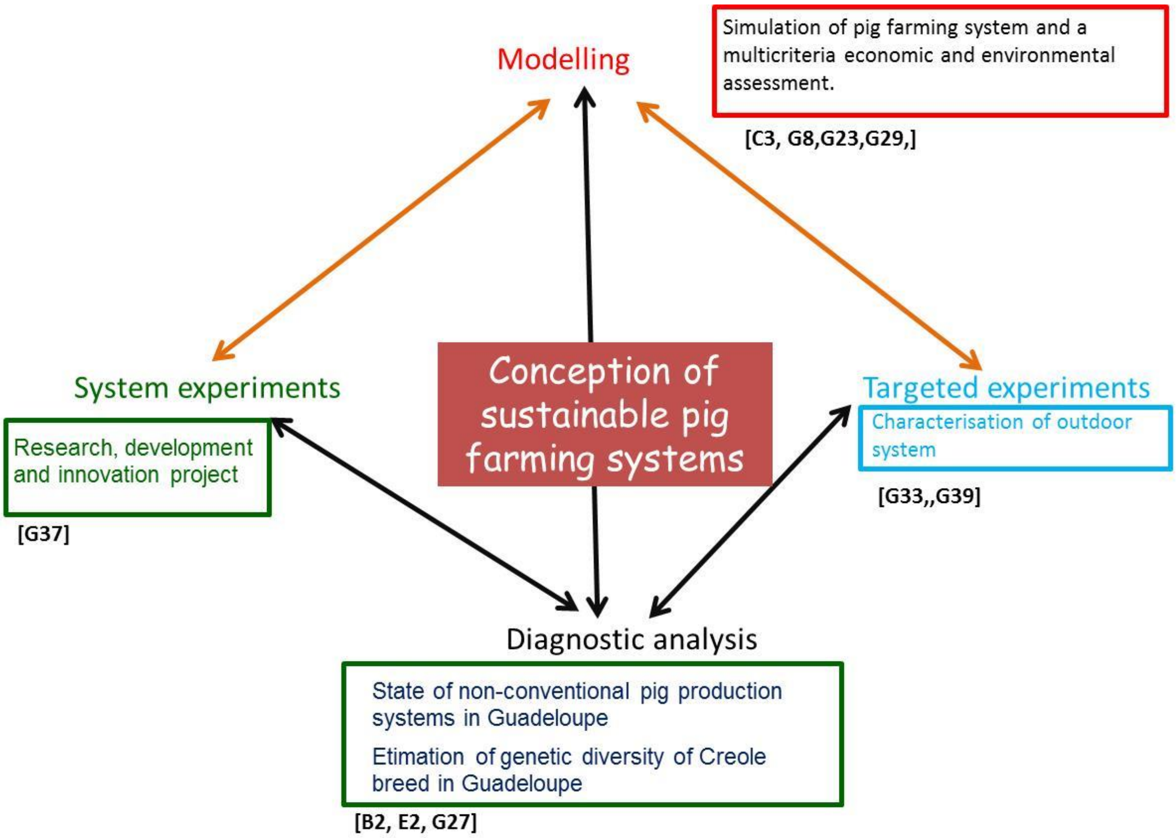
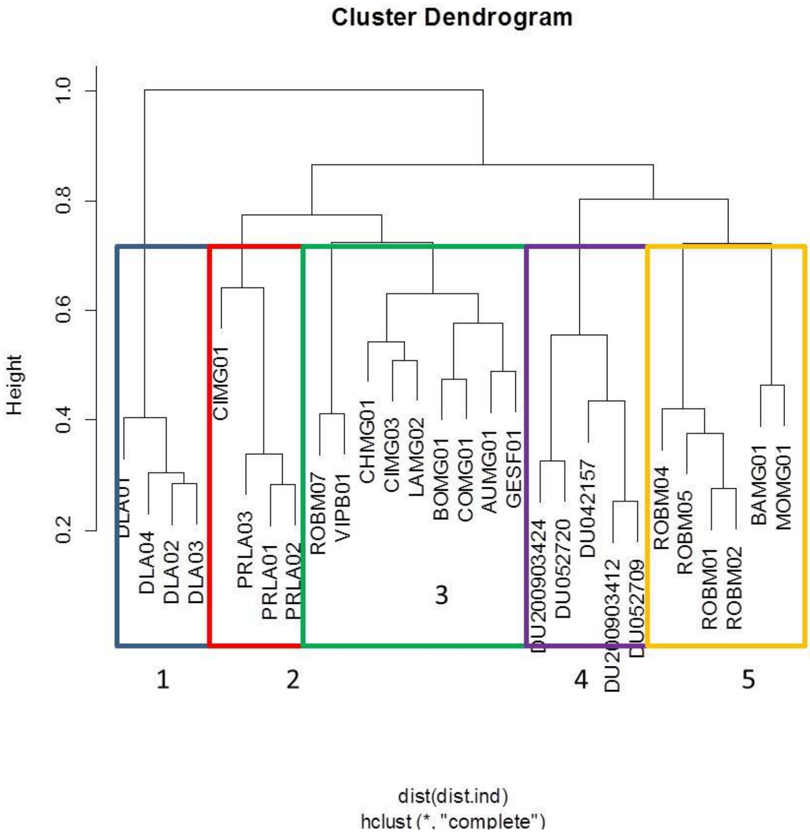


Figure 28. Dendogram from clustering classification of genotypes (via 36 microsatellites) of 28 Creole pigs from 15 diverse locations of Creole pig herds in Guadeloupe mainland and Marie-Galante (from **[G27])**.



Photos 1. Illustration of the level of soil cover before and after the passage of pigs (adapted from **[G33]**).

TABLES

Table 1. List of macro biomarkers of heat tolerance use in livestock studies.

Biomarkers	Category	Sub category
Rectal temperature	Heat resistance	Thermoregulation
Respiratory rate	Heat resistance	Latent heat loss
Skin temperature	Heat resistance	Sensible heat loss
Production traits as a function of heat load	Heat resilience	Heat production
Reproduction traits as a function of heat load	Heat resilience	Heat production
Feed intake	Heat resilience	Heat production

Table 2. Effect of temperature-humidity index on performance and body temperatures of growing pigs raised in a tropical humid climate (adapted from [G15]).

	THI<25°C	25°C≤THI≤27°C	THI > 27°C	Significance
Rectal temperature, °C	39.6^{a}	39.6^{a}	39.7^{b}	THI**, Sx**, BW**, S*
Cutaneous temperature, °C	36.3^{a}	36.7^{b}	37.0^{c}	THI**, BW**, S*
Thermal circulation index	3.0^{a}	3.1^{a}	2.8^{b}	THI**, Sx**, BW**, S*
Number of meals	10.4^{a}	9.4^{b}	8.4^{c}	THI**
Average daily feed intake, kg/j	2.04^{a}	2.09^{a}	1.90^{b}	THI**, BW**
Ingestion time, min/j	86.4^{a}	78.6^{b}	76.9^{c}	THI**

From an analysis of variance including the effect of THI, sex (Sx), sire (S) and the BW as a covariate and the effect of pig as random effect to account for repeated measurements on the same animal.

Table 3. Effect of rearing conditions on production and thermoregulatory responses of Large White and Creole growing pigs fed with the same diet (adapted from [G39,H12]).

	Indoor (THI=23.6°C)		Outdoor (THI = 25.3°C)		Significance
	Large White	Creole	Large White	Creole	
Cutaneous temperature, °C	35.8[a]	35.0[b]	38.1[c]	37.3[d]	B**, R*
Rectal temperature, °C	39.9[a]	39.2[b]	39.9[a]	39.9[a]	BxR*
Average daily gain, g/d	390[a]	340[b]	250[c]	280[d]	BxR*

From an analysis of variance including the effect of breed (B) and rearing system (R) as fixed effects and the effect of pig as random effect to account for repeated measurements on the same animal.

Table 4. Heritabilities ($h^2 \pm$ SE) of rectal temperature in different livestock species. (adapted from (Renaudeau et al., 2004) and [A24]).

Species	Physiological stage	No.[1]	h^2	References
Bovine	post-weaning	192	0.11 ± 0.16	(Da Silva 1973)
Bovine	adult cow	1700	0.25 ± 0.12	(Turner 1982).
Bovine	15 months of age	611	0.19 ± 0.13	(Morris et al., 1989)
Bovine	post-weaning	1341	0.19 ± 0.02	(Mackinnon et al., 1991)
Bovine	birth to 18 months of age	NA[2]	0.12 ± 0.03	(Prayaga and Henshall, 2005)
Bovine	lactating cow	1695	0.17 ± 0.13	(Dikmen et al., 2012)
Poultry	birth to 7 days of age	161	0.36 ± 0.18	(Taouis et al., 2002)
Pig	lactating sow	697	0.35 ± 0.09	Our study [A24]

[1] No : number of observations used for heritability estimation; NA: not available

Table 5. Heritabilities ($h^2 \pm SE$), phenotypic (below the diagonal) and genetic (above the diagonal) correlations of lactating performance and thermoregulation traits[1] of Large White lactating sows in tropical humid climate. (adapted from [A24]).

	ADFI	BWc	LBWg	RT	CT	RR
ADFI	**0.25 ± 0.08-**	**-0.80 ± 0.14**	**0.25 ± 0.11**	0.07 ± 0.20	0.31 ± 0.24	**0.35 ± 0.12**
BWc	**-0.36 ± 0.04**	**0.20 ± 0.07**	**0.59 ± 0.20**	-0.01 ± 0.15	-0.06 ± 0.27	-0.25 ± 0.22
LBWg	0.03 ± 0.06	**0.10 ± 0.05**	**0.31 ± 0.09**	0.30 ± 0.18	0.10 ± 0.26	0.13 ± 0.15
RT	-0.03 ± 0.05	0.05 ± 0.05	**0.10 ± 0.05**	**0.35 ± 0.09**	**0.72 ± 0.10**	**0.25 ± 0.12**
CT	0.08 ± 0.06	-0.05 ± 0.07	0.05 ± 0.09	**0.49 ± 0.06**	**0.34 ± 0.12**	**0.46 ± 0.22**
RR	**0.27 ± 0.06**	**-0.14 ± 0.07**	0.05 ± 0.08	**0.24 ± 0.07**	**0.28 ± 0.07**	**0.35 ± 0.13**

[1] ADFI: average daily feed intake; BWc: proportion of BW change during lactation; LBWg : Litter BW gain; RT: Rectal temperature; CT: Cutaneous temperature; RR: Respiratory rate Bold values significantly differ from zero ($P < 0.05$)

Table 6. SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis of the management of the Creole pig breeding schemes (adapted from **[E1]**).

Weak points : • low population size • low number of farmers • expensive products • lack of identity and trait records from many animals • important traits missing in the genetic evaluation (health, meat quality, ability to use fibrous feed...) • no AI, difficultty to evaluate animals in different herds	**Strong points** • genetically unique breed • favourable economic context for increased Creole pork production • favourable social context for increased Creole pork production • high quality product • animals well adapted to the environment • pigs valorise by-products in small scale production systems and mixed farming systems • framework for cryo-conservation of semen
Threats • extinction of the whole population, due to low number of animals • increase of inbreeding leads to weaker animals, higher mortality • risk of losing the whole population in an infectious disease, due to exchange of live animals • the farmers might lose interest in this production	**Opportunities** • dynamic group of farmers • possibility to build a strong label for marketing • possibility to achieve support from EU, France and local authorities • enthusiastic customers and volunteers engaged in marketing

APPENDIX

APPENDIX 1 : LIST OF PUBLICATIONS

Research articles published in journals indexed ESI (Essential Science Indicators)

A1 **Gourdine, J. L.**, D. Renaudeau, J. Noblet and J. P. Bidanel. (2004). Effects of season and parity on performance of lactating sows in a tropical climate. Animal Science, 79: 273-282 (became *Animal)*

A2 **Gourdine, J. L.**, D. Renaudeau, C. Anaïs, K. Benony and B. Bocage. (2005).A comparison of performance of lactating Creole and Large White sows in tropical humid climate: preliminary results. Archivos de Zootecnia 54:423-428.

A3 **Gourdine J-L**, Quesnel, H, Bidanel J-P and Renaudeau D. (2006). Effect of season, parity and lactation on reproductive performance of sows in a tropical humid climate. Asian-Australiasian Journal of Animal Science. 19: 1111-1119.

A4 **Gourdine J.L.**, Bidanel J.P., Noblet J., Renaudeau D. (2006). Effect of breed and season on performance of lactating sows in a tropical humid climate. Journal of Animal Science, 84: 360-369.

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2. **Gourdine J-L**. 2006. Analyse des facteurs limitant les performances de reproduction des truies élevées sous un milieu tropical humide. Thèse doctorale de l'Institut National Agronomique Paris-Grignon (became AgroParisTech). 186 p

APPENDIX 2 : TABLE OF DEFINITIONS

- **AgroParisTech:** Paris Institute of technology for life, food and environmental sciences (http://www.agroparistech.fr/Presentation-of-AgroParisTech.html).

- **INRA**: Institut National de la Recherche Agronomique (the French National Institute for Agricultural Research). In today's complex climatic, demographic and energy context, agricultural research must deal with major issues on various scales. Preparing worldwide food availability and security by 2050, reducing greenhouse gas emissions from agriculture, and promoting alternative agricultural and forestry practices that can respond to non-reversible climate change are challenges the entire world must face. Some of the many underlying concerns that must be tackled include understanding individual behaviour on a regional or market level; studying the relationships between plant, animal and human health; researching new ways of producing energy and materials from agricultural sources; and limiting overall environmental impacts To deal with these issues, **INRA** produces scientific knowledge and works for economic and social innovation in the areas of food, agriculture and the environment. (http://www.inra.fr/en/)

- **PTEA** : Plateforme Tropicale d'Expérimentation sur l'Animal. PTEA is the only tropical experimental unit of the Animal Genetics Division of **INRA**. PTEA is conducting the **INRA URZ** major experimental designs. The pig herd of approximately 70 sows is part of many research programs. **PTEA** team is particularly qualified for pig, beef cattle, goat and sheep animal breeding and production trait measurements. **PTEA** is also involved in the collection of biological samples for various experimental needs; tail or blood samples collected in the farm for DNA extraction, urine samples, and post-mortem sampling of tissues.

- **QTL** : Quantitative trait loci. A QTL is a region of the DNA sequence that is found to have a n effect on a quantitative trait.

- **REML** : Restricted/Residual Maximum Likelihood. REML is a statistical method of maximum likelihood estimation. In contrast to the traditional maximum likelihood approach, REML can produce unbiased estimates of variance and covariance parameters.

- **SNP**: Single Nucleotide Polymorphism. As suggested by the acronym, an SNP marker is a single base change in a DNA sequence, with a usual alternative of two possible nucleotides at a given position. For such a base position with sequence alternatives in genomic DNA to be considered as an SNP, it is considered that the least frequent allele should have a frequency of 1% or greater. Although in principle, at each position of a sequence stretch, any of the four possible nucleotide bases can be present, SNPs are usually biallelic in practice (Source Vignal et al. (2002). Genet. Sel. Evol. 34 : 275-305).

- **SOSPIG**: Sauvegarde Organisée et Sélection des Porcs Indigènes de Guadeloupe. SOSPIG is an association of farmers. The aim of this breeder association is promoting and maintaining indigenous pig breed in Guadeloupe.

- **THI**: Thermal humidity index. The THI allows combining in one function the effect of temperature and relative humidity and their interaction. There are several formulae available. We choose the following formulae: THI[°C) = T –(0.55 – 0.0055 x RH) x (T – 14.5). This formula was proposed by NOAA (1976; cited by Zumbach et al. (2008)), where T is the average daily ambient temperature (°C) and RH is the average daily relative humidity.

- **URZ** : Unité de Recherches Zootechniques (. **URZ** is located in Guadeloupe (French West .Indies), and it is the only tropical research unit of the Animal Genetics Division of **INRA**. It aim is to promote sustainable animal production in the tropics within an agroecological perspective, by valorizing adaptive and resilience abilities of livestock and farming systems to biophysical and socio-economic constraints. **URZ** has a long experience in the study of heat stress related to tropical seasonal variation or artificial thermal challenge on sensible and adapted genotypes (breeds coming from Europe vs. local breed). **URZ** has a laboratory for chemical analysis and collection of biological samples and **URZ** is also involved in the secured conservation of samples through the tropical biological resources center (CRB). **URZ** works in close collaboration with **INRA PTEA** from which animal production and measurements are performed.

APPENDIX 3 : CURRICULUM VITAE

GOURDINE Jean-Luc
French citizen, born on September 6th 1975 ; Abymes (Guadeloupe, F.W.I)
Married, 1 child
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Current situation
Research engineer in animal experiments at INRA – URZ, Unité de Recherches Zootechniques, 97110 Petit-Bourg Associated member of Centre d'Etude et de Recherche en Economie, Gestion, Modélisation et Informatique Appliquée (CEREGMIA)

Education
Scolar: 2000-2002 : MSc in Applied Mathematics and Biostatistics (University of Montpellier II, France) 2002-2003 : Civilian voluntary work to technical assistance (INRA-URZ, Guadeloupe) 2003-2006. Ph.D. in Animal genetic and adaptation (INA P-G – since 2007, AgroParisTech Institute) *Other :* 2003. High level course in genetic improvement of livestock, session « pig production » 2009. Courses in the framework of my Post-doc at University of Uppsalla (Sweden) « Basic principles in Animal Molecular Biology » 2012. Research school « Genomic management of animal genetic resources in hot regions » 2013. Courses in statistical analysis of genomic data (expression dataset) and workshop in the framework of the ANR-project Rules & Tools : « Statistical methods to dissect variability of traits using SNP chips.».

INRA situation
August 2006. Recruitment as a researcher engineer at the INRA-URZ Current research programs : 1/ Genetic variability of pig's adaptation to heat 2/ Conception and evaluation of pig production system in the tropics

Scientific production
33 articles published in journal with reviewers committee. 2 book chapter 2 research reports 41 communications in congress 12 students reports

Teaching activities
Supervision of students: 10 Master students Member of the Ph.D. committee of X. Xandé (2008, University of French West Indies and Guiana) Member of the Ph.D. committee of M Gunia (2012, AgroParisTech) Co-supervisor of the Ph.D. student R. Rosé (she begun in 2014, University of French West Indies)

Teaching :
2007. Applied statistics in Biology (40h), Bachelor in Biology (University of French West Indies and Guina)
2007-2009-2012. Workshop in Introduction to Statistic (42 h / year), technicians from INRA and CIRAD
2010-2015. Introduction to quantitative genetics and introduction to systemic modelling (7.5 h / year), Master in Mathematics (University of French West Indies and Guyana)
2012. Applied statistics to genomic (15 h), Master in Biology and Health
2006-2015. Technical meeting (breeding associations in Guadeloupe, Martinique, Réunion)

Administrative activities :
Elected member of the Scientific Council of the INRA French West Indies and Guiana center.
Member of the French West Indies and Guiana Ethic Committee in animal experiments (CEMAAG)
Member of the Guadeloupe rural network
Member of the association for the preservation of indigenous pigs in Guadeloupe e (SOSPIG)
Member of the French association of Animal Production (AFZ)
Member of the French Society of Statistic (SFdS)

Funds

- Participation to the Contract « State-Region Plane 2001-2006 » (Biodiversity of animal productions) and 2007-2013 (Agro ecology of multispecies systems for the development of sustainable agriculture in tropical environment) directly managed by INRA-URZ
- Participation to a Project funded by the French Oversea Ministry« Valorizing and conservation of the biodiversity in Creole breeds », 2011 : leader of the task "Creole pig".
- Participation to the European project EU-Q-PorkChains in the framework of my Post-Doc: participation to the task « Breeding pigs for sustainable production » (2008-2010)
- Participation to the INRA metaprogram ACCAF : project PIGCHANGE : participation to the task on genetic solutions to mitigate the effects of heat stress
- Participation to the European project ANIMALCHANGE (2011-2014): participation to the task 7.3 of the WP 7 on the evaluation of the consequences of climate change on pig production
- Participation to the French ANR-Project « GAIA-TROP », Viability and Adaptative Governance of Tropical Insular Agro system: participation to the task on adptative ability of farming systems (2013-2017)
- Coordinating of two small projects funded by the INRA Animal Genetics Department in 2011 (AAP-GA 2011 : implementation of the experimental design and phenotypic analysis of F1 population) and in 2012(AAP-GA 2012 : PhenoHeaT : High throughout phenotype of thermoregulatory responses in farming conditions)
- Coordinating the French ANR-project « PigHeaT » Pig Heat Tolerance: Adaptation to heat in pig production : the genetic pathway (2012-2016)