# The Character of Inca and Andean Agriculture

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## *1. Introduction.*[1]

There is an apparent enigma that underlies most discussion of Andean agriculture: How did the Incas manage to produce the enormous agricultural yields as reported in the chronicles of Cieza de León and others and confirmed by archaeological work (Morris 1981: 327-406)? On the other hand, why have nearly all attempts to raise the productivity of high mountain slope fields with exclusively western technology (colonial and modern) failed? For a first approximation it should be noted that the great majority of (ex) haciendas were located: on the flat coastal riverine areas; on the wider inter-Andean valley bottoms (Mantaro, Cajamarca, Cochabamba, etc.); and in certain areas of the plains of the high punas which are mostly used for pastoral activity rather than for cropping. These are precisely the parts of the Andes, which are less typical of the environment than the rugged sloped areas where the majority of Indian peasant communities are located today. Only in those atypical areas have exclusively western type agricultural strategies (which nowadays are associated with machinery, mono-cultivation, etc.) been implemented with success[2]. In this paper some of the reasons for this seemingly enigmatic circumstance will be brought out.

Many writers beginning with some of the chroniclers and continued by anthropologists, archaeologists, historians, agronomists, and others to the present day have recognized that there is a certain "special character" to Inca agriculture. In this paper I will show that this "special character" has much to do with the nature of the climatic conditions at high altitudes in the Andean tropical zone and the organizational patterns associated with it. One of the first systematic attempts to interpret the character and evolution of Andean civilization in relation to the structure of the environment was due to Carl Troll (1980); his work has been a constant source of inspiration for many students of this problem including the present author. The key characteristic of this environment is best expressed by one term -- diversity. I do not maintain that Inca and the environment determines Andean culture, but as Flannery et al (1991) have put it -- culture is not adaptively neutral. The ecoclimatic situation at high altitudes places constraints on what can be done and what can not. A viable agricultural system in the Andean environment is one that can maintain its own stability in face of the very high uncertainty generated by this diversity. In the first part of this paper I will discuss this diversity and the main physical principles that underlie it. I will first give a brief account of the spatial diversity the Andean climatic gradients that are associated with it. Following this the factor of temporal diversity, and risk, will be discussed.

In the second section I will discuss the strategies of ecoclimatic uncertainty management that were incorporated into Inca socio-economic organization, and something of their preinca development. -- many of which continue to be employed in the modern Andean indigenous communities. In the third section I will go on to describe how a continual practice of experimentation is a requisite for agricultural viability in the Andes and describe some results of my study of the Inca agricultural experimental site of Moray. In the course of the discussion of these points what I mean by the character of Inca and Andean agriculture will become clear.

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1 Ponencia dada en Israel ... el año 1998 auspiciado por la PUCP y la Embajada del Perú en Israel.

2 In those uneven and steep sloped areas where haciendas did hold on until the Agrarian Reform of the late 60s and 70s, these were not managed directly by the owners. Instead, they were worked by traditional Andean techniques carried out by the Indians who lived in them. Every year the owners received a proportion of the crop. The Indians worked the hacienda lands in accord with a system of "turns" (*mita*) which had its origins in the prehispanic organization. Thus these hacienda are better seen as a particular form of Andean agriculture adapted to the hacienda system rather than an implementation of European agriculture.

## *2. Ecoclimatology at high altitudes.*

There are a number of climatic gradients that give rise to the ecoclimatic conditions in the high sierra of the central south Peruvian Andes, conditions that are very different to those near to sea level. The atmospheric conditions on the desert coast and in the tropical rain forest are characterized by high humidity and reduced diurnal fluctuations. At high altitudes the air is generally dry and the evapotranspiration is high.

A good idea of the spatial climatic diversity in the tropical Andes can be gained from the Holdridge "Life Zone" classification of the world's ecoclimatic systems. According to this scheme the world's ecologies are grouped into 104 life zones (Holdridge 1947). Put very simply, the life zones are defined in terms of the intersection of three factors: the temperature, the precipitation, and the evapotranspiration. A particular class of plant associations characterizes each life zone. Applying this scheme to Peru Joseph Tosi defined 84 life zones distributed throughout the country (Tosi y ONERN 1978). Thus Peru, with only 0.86% of world's land area counts with 80% of its zones, has by far the greatest ecoclimatic diversity per unit area of any country in the world. Flannery, Marcus and ...(1989) write:

> *"So complex are the environmental gradients between snow capped mountain peaks and the riverine floor of the basin that all published descriptions are simplifications. The human mind typically reduces a daunting mass of environmental information to a set of model or ideal categories, and this is as true for the Western ecologists who have studied the Andes as it is for the Indians.*

As the above quote implies the complexity is much greater than any classification we can come up with. It happens that the life zones, or any other ecological groupings, form a mosaic across the area. The zones are distributed discontinuously and the visible number and positioning of zones depends on the scale of resolution employed. The published ecology map of Peru (Tosi y ONERN 1975) is at a scale of 1:1,000,000. At a scale of 1:100,000 most of the zones depicted at the highest scale would open up into a mosaic of smaller ones, it would happen that the one labeled at the large scale would be the most representative, but it would be intermingled with many other smaller zones. My experience indicates that the same breakdown would be repeated again at a resolution of 1:10,000. In fact my current research in Bolivia suggests that there is a fractal self-affine reiteration process involved, just as there is in the patterning of a coastline at different resolution levels. At each level the pattern is much the same though there are differences in the details. In the more central Peruvian Andes where the terrain is more rugged and the number of visible resolution levels would increase.

I will now briefly discuss the ecoclimatic gradients that give rise to so much diversity in the Andes.

### 2.1 The atmospheric pressure gradient.

Air pressure at sea level is approximately 1013 millibars (mb), and falls off with altitude according to a function which in the altitude range of the Andes can be treated as linear. The approximate air pressure from sea level to 5,500m is given in the table 1. At 5,500m the pressure is about half of its value at sea level.

| ALTITUDE | APPROXIMATE BAROMETRIC PRESSURE (mb) |
|---|---|
| 0 | 1013 |
| 1,000 | 895 |
| 2,000 | 795 |
| 3,000 | 700 |
| 4,000 | 620 |
| 5,000 | 550 |
| 5,500 | 515 |

Table 1
Altitude and air pressure

## 2.2 The solar radiation gradient

The suspended dust and pollution in the air at lower altitudes makes it meaningless to talk in terms of general trends like the air pressure. However a reasonable number of experimental registers have been carried out in the Sierra. For the region of Ayacucho a good empirical approximation is given by Swiss physicist P. Ambrossetti (1979) for the layer from 2,000m to 4,000m above sea level in the short wave band 0.3 -- 3µ. The following graph (Figure 1) gives the energy of the incoming direct radiation at midday for the periods when the sun passes near the zenith point at 13º latitude when the direct radiation reaches 1.63cal/cm$^2$/min. The global radiation[3] reaches a value of 1.7 cal/cm$^2$ min. On completely clouded days the global radiation drops to half the value, however over the whole year its value is nearly constant at a little below 0.8 cal/cm$^2$.min. While the average hours of direct solar exposition fall to some 50% of the theoretically possible in the rainy season the average daily global radiation is nearly 90% of the clear sky value in the same months. This is because the atmospheric (Raleigh) diffused radiation is a greatest at shorter wavelengths. (If this were not so we would find it difficult to see on cloudy days.) While the empirical equation used may seem to give exaggerated results, Grace (1983: 113-5) has recorded 1.72 cal/cm$^2$/min in Puno at 3,852m altitude. The surprising fact is that high altitude radiation with clear skies is much nearer the value of the solar constant[4] than it is to the values registered near sea level near Lima.

[3] The global radiation is the sum of the direct radiation and the short wave diffuse radiation.
4 The solar constant is the solar radiation received out side of the Earth's atmosphere. Observations by satellite show that it varies from about 1.93 to 1.98 cal/cm$^2$/.min depending on the energetic behaviour of the Sun itself.

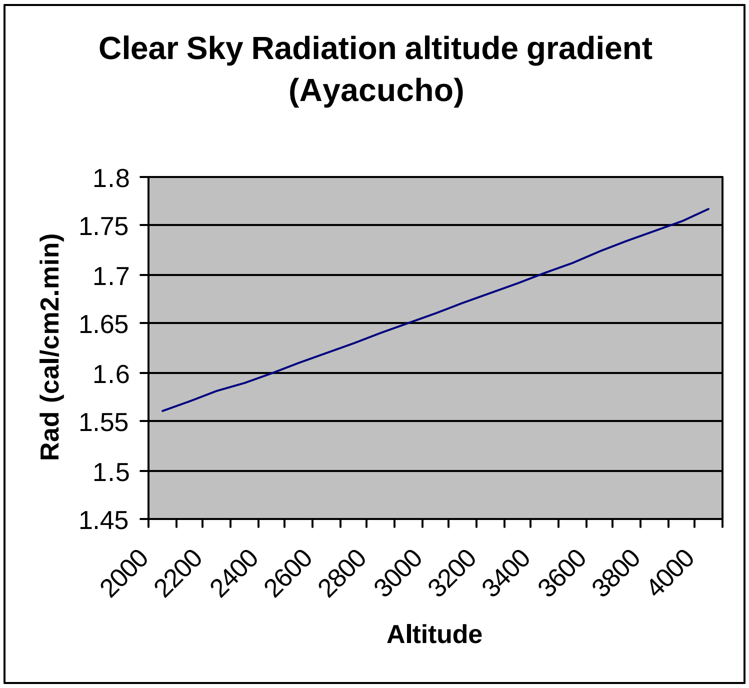


Figure 1.

The incoming solar radiation gradient is related to the atmospheric pressure gradient. The thinner air at higher altitudes makes is unable to trap and retain as much energy of the incoming solar radiation as at lower altitudes so that the air is cooler and the ground hotter in the sunlight The low air density also enhances the outgoing nocturnal emitted thermal radiation. “The microclimate of high levels [altitudes] is consequently not only more extreme in its higher heat reception by day, but also its greater heat loss by night.” (Geiger 1951: 21).

## 2.3 The temperature gradient

In the south central Andes of Peru air temperature (recorded at 1.5m above ground) drops off by 6.4ºC per km altitude during the relatively dry planting season and a degree less in the wetter months. In Figure 2 I have graphed mean temperatures for a period of 20 years for 24 stations located in the inter-Andean areas of the Departments of Ayacucho, Apurímac, Cusco and Huancavelica[5] for the month of October (SENAMHI 1989). The correlation between the average minimum, mean and maximum air temperatures with altitude are clear. Nevertheless, there is no correlation of the average diurnal range of temperatures with altitude, as would be expected from theoretical considerations. This is due to the great influence of the topoclimatic particularities of the local mesoenvironments.

[5] The stations were chosen to express the climatic conditions of the areas with very high concentrations of Indian peasant communities.

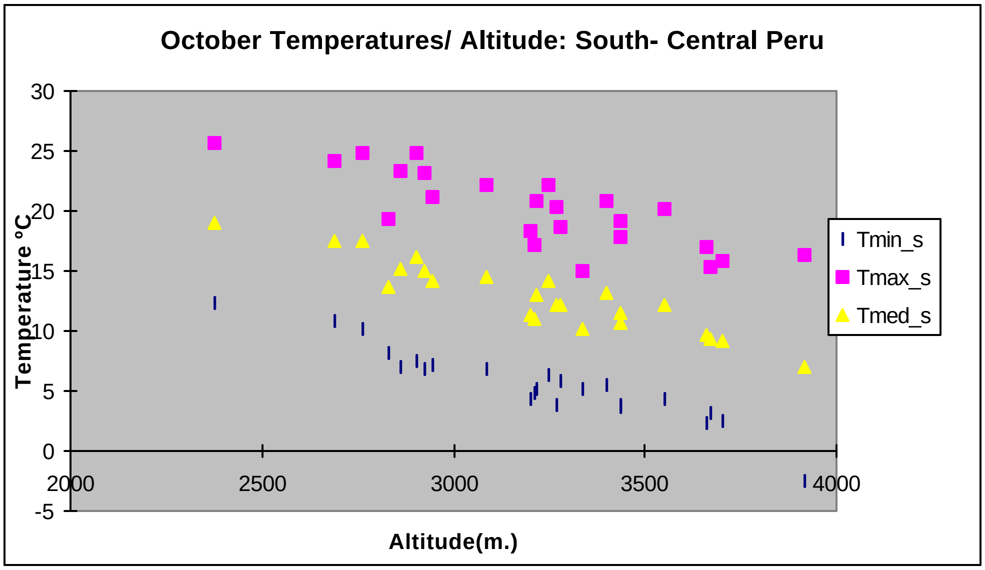


Figure. 2.

## 2.4 Air humidity.

The amount of water vapor, *e*, in the air decreases with altitude because of diminished air pressures and temperatures. However since the saturated vapor pressure, $e_s$, is fundamentally a function of temperature, and so decreases with altitude, the vapor pressure deficit, $e_d = e_s - e$, decreases much more slowly. In Figure 3 I have graphed the values registered for $e_d$ and *e* for nine inter-Andean stations commensurate with the above geographic and social conditions but where the humidity has been registered by psychrometer (Frére, Rea y Rijks 1975). Due to the lack of readily available data I have included two stations in the Altiplano and mountain regions of Puno to get a minimal statistically representative sample. For the highest station, Paucarani at 4,541m above sea level, the mean values of $e_d$ and *e* are equal at 3.5mb where the two tendency lines intersect. The above authors make the point that when the water vapor saturation is calculated in terms of the minimum temperatures, the values obtained for *e* are about the same as those for $e_s$ calculated for the minimum temperatures. This implies that the humidity at high altitudes is "driven" by the minimum air temperatures. In the humid coastal regions the difference between Tmin and Tmax averages only about 6 or 7ºC, while at high altitudes diurnal fluctuations average at about 15ºC.

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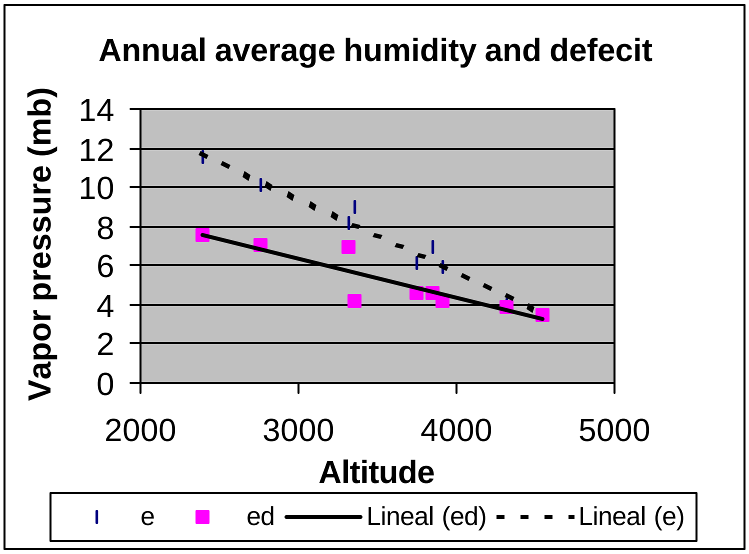


Figure 3

## 2.5 Altitude and uncertainty

At high altitudes climatic variability is much greater than at lower altitudes. Rudolf Geiger pointed out that in the higher mountain regions with lower atmospheric and water vapor density, and with higher solar radiation and thermal counter radiation than at sea level (see above), the ground temperatures are a much more important influence on plant growth than the air temperature is. Quite different microclimates can coexist side by side because relatively small differences in soil composition, colour and texture, sun / shade variability, etc., diminish the homogenizing effects of thermal advection and conduction.

Small differences in ground temperature give rise to pronounced differences in the metabolic processes of plants and in the duration of their vegetative cycles. To quote again from Geiger:

> *"In high mountains with their low temperatures, the plant world can thrive only close to the ground, and the amount by which the ground temperature exceeds the air temperature increases with altitude."* Geiger (1959:35*).*

## 2.6 Uncertainty and predictability

B. Winterhalder (1988) has carried out very important and original systematic research on the theme of Andean ecoclimatology and predictability. I will discuss the problem of Andean temporal uncertainty in terms of this scientist's study.

Winterhalder's work focused on the seeming incongruence of vast systems of irrigated agricultural terraces in the Western slopes (e.g. the Valley of Colca) and vast systems of unirrigated terraces on the Eastern slopes (Sandia). His interest lay in determining to what extent this very important agricultural technological difference could be explained in terms of the different climatic regimes. To mark the onset and conclusion of the natural climatically adequate agricultural seasons he set, somewhat arbitrary as he admits a monthly rainfall ≥ 64mm and a minimum temperature ≥ 0ºC.

He copied the existing data on monthly rainfall and temperatures for 84 stations from the registers of SENAMHI. These stations are located close to the transect drawn perpendicular to the axis of the Andean cordillera in the Departments of Arequipa, Cusco and Puno southern Peru. They cover the altitude range from close to sea level to 4,600m of the three geoecological provinces termed the dry Western Escarpment, Altiplano and the wet Eastern Escarpment. His index of predictability ranges from 0 for completely unpredictable conditions to 1 for completely predictable[6]. The index has two subcomponents: constancy expressing interannual variability, and contingency, which expresses month to month variability for a seasonal scale. Here I will only discuss the compound predictability index.

Winterhalder's analysis of his data shows that for the Western Escarpment (from lowland coastal desert to the watershed divide) the rainfall increases with altitude while the minimum temperatures decrease. On the other hand the rainfall decreases with altitude in the Eastern Escarpment (from the eastern watershed divide to the lowland rain forest) and while the air temperature decreases for the same altitude it is a few degrees lower than for the Western. In both cases the regressions are significant well beyond the 1% probability level. For the Altiplano region the regression of precipitation on altitude lacks statistical significance, this would be basically due to the fact that the local topographical effects mask the more general relation to altitude. For the eastern Altiplano I have registered a precipitation of 75mm for the month of November 1997 in one station at 4,100m while in another one less than one kilometer distant at 3,960m the fall was only 15mm. On the other hand the temperatures show the same high correlation with altitude as would be expected from figure 3

The regressions made by Winterhalder of the derived predictability indices for precipitation on altitude for both regions are significant to the same levels as those for the precipitation[7].

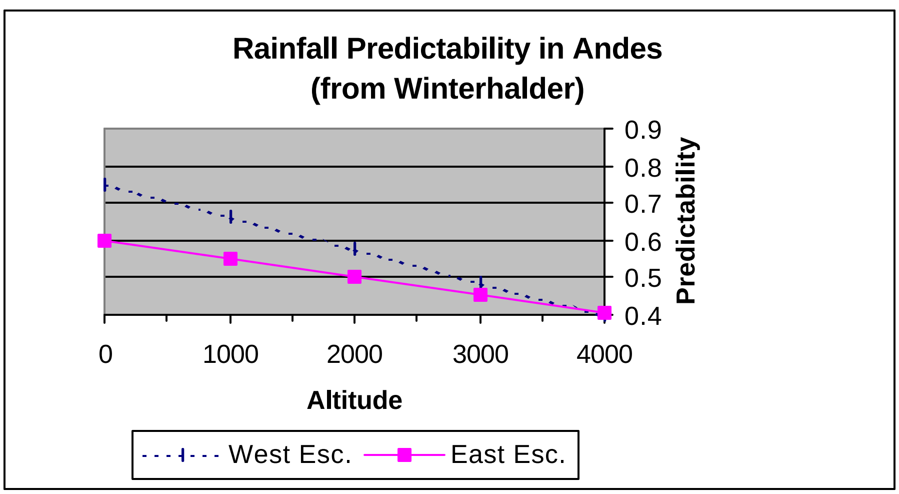


Figure 5.

In figure 5 I have graphed the rainfall predictability index using Winterhalder's linear regression equations for both the Eastern and Western Escarpments. It is important that for both geoecological

[6] It is worth commentating that this predictability index has much in common with the measure of redundancy as defined by Shannon in information theory. It will be worthwhile to analyze this in future work.
[7] It is very interesting that he finds a polynomial quadratic regression gives a much better fit for the precipitation/ altitude on the Western Escarpment than does a lineal one. I can only say that this is yet another factor that demonstrates our ignorance of Andean ecoclimatology.

regions the predictability diminishes in spite of the fact that the corresponding overall pluvial gradients are inverted. Pluvial uncertainty increases with altitude – more rapidly on the western slopes than on the eastern because of the much greater overall wetness of the latter – but at 4,000m both converge to the value of 0.4. For the Altiplano region the indices for both rainfall and minimum temperature show no correlation with altitude, the pluvial predictability across the Altiplano is pretty regular with a value of just over 0.5. The data for the Western Escarpment lead Winterhalder to the convincing conclusion that at high altitudes irrigation is employed to reduce monthly irregularities in the distribution of water. Irrigation on the coast is obviously used for quite different reasons – it is very predictable that with the exception of the years of El Niño there will be virtually no rain.

With respect to the predictability of minimum temperature the picture is similar. Winterhalder chose the value of Tmin ≥ 0ºC because at lower temperatures the certainty of frost makes the sowing of most crops unfeasible. In Figure 6 the relation of Tmin with altitude is graphed for both escarpments.

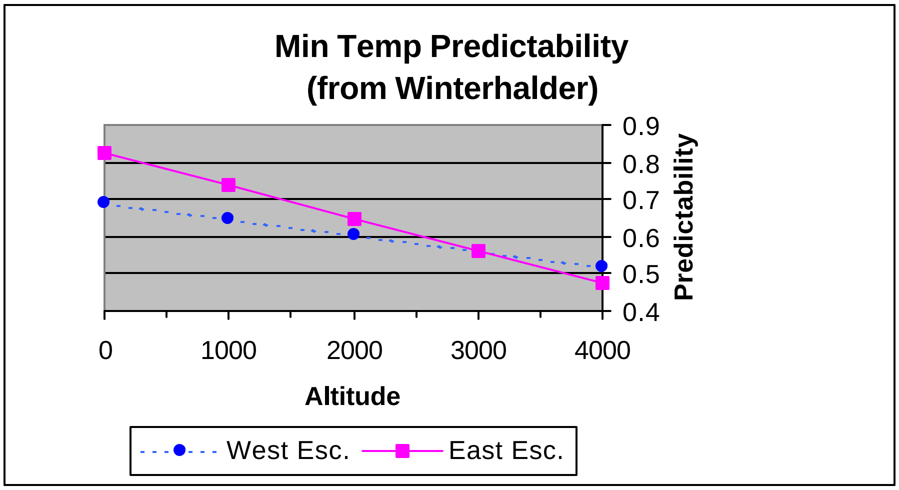


Figure 6.

The picture is much the same for minimum temperature uncertainty as it is for precipitation, with the important difference that predictability diminishes more sharply on the Eastern Escarpment than it does on the Western.

Winterhalder goes on to discuss the onset and conclusion of the agricultural seasons at different altitudes of the Andes in terms of the results given out above. The agricultural season is defined by the thermal and water availability constraints. In the lowest parts of the Eastern Escarpment the rainy season, as defined above, lasts the whole twelve months. It becomes shorter as altitude increases and is reduced to some five to six months in the Altiplano over to the middle altitudes of the Western slopes; below which it rapidly drops off to zero for the lower slopes of Arequipa. For most of the eastern areas, the Altiplano and the upper western escarpment the period of adequate precipitation is contained within the period of adequate thermal conditions – though only just at the highest regions and in the upper part of the western slopes. From 4,000 to 3,000m on the western slope the rainy season drops from 3 to 4 months to 0 months duration, just as the thermal season expands rapidly to nearly 12 months. As he puts it: "The abundant water of the highest elevations is moved a short distance down slope to favourable thermal conditions, where it can augment the quantity and duration of the quite restricted rain".

I shall leave this scientist's discussion of his results for the next section of this paper in which the central theme is of the basic strategies employed by the Inca State and the preincaic polities that developed them. In part because he comes to similar conclusions to those which I have advanced in previous publications, and in part because of the results of my ongoing research into water management in the eastern Altiplano and adjacent valleys. It will be necessary to discuss some of the archaeological, ethno-historical and ethnographic evidence to arrive at more general conclusions.

### 2.7 A general ecoclimatic conclusion for the Andes

In the light of the above discussions a general conclusion is made. In the first place there is the increase in spatial and temporal diversity with altitude in the Andes. This can be explained in terms of the factors pointed out by Geiger and aptly illustrated by Winterhalder's and other's works. The low pressure and dryness of the air reduces the interaction of the high incoming radiation photons with the air molecules – a greater proportion of these photons interact directly with the ground surface than at low altitudes. Thus the differences in the, colour, humidity and texture of the surface with their different reflectivity (albedo) are translated into significant surface temperature differentiation and a corresponding differentiation in the biomass cover. In the night, the height of the apparent horizon (including any nearby bushes and trees), the surface albedo in the infrared thermal band, and the degree of cloudiness of the sky, determine the probability of frosts[8].

The mountain environment gives rise to vigorous and rapid temperature fluctuations. A passing cloud causes the air temperature to fall some 10 to 15ºC within minutes and 20ºC diurnal variations are quite normal. Above an altitude of approximately 2,200m there is no time of the year completely free of frosts. If Winterhalder had been able to use surface temperatures instead of air temperatures for his study he would certainly have found more pronounced uncertainty indices than those deduced for the air temperatures.

## *3 Technologies of risk management: the strategy of massive parallelism.*

What I call "massive parallelism" (this is an expression I have borrowed from computer terminology, its meaning will be made clear at the end of the paper, for the moment it can be thought of as the undertaking of many different measures to cope with possible contingencies) in the Andes takes many forms. One of the best known is that of having access to the greatest number of fields (*chacras*) and crops possible and in as wider range different of eco-climatic conditions as possible; it is not unusual for a family to have up to 30 or more dispersed *chacras*. In this way they can be assured that when there is a crop failure in some places the overall yield will cover the loss – it is taken for granted that something will be lost somewhere in the climatic uncertainty of the Andes. Multiple cropping in the same *chacra* nearly universal – some plants resist unfavourable conditions better than others – but since one can never be sure of just what conditions are going to come about it is logical to sow crop associations made up of plants with different sorts of resistance to different forms of stress. This tactic is probably very ancient and helps to explain the tremendous range of domesticated food crops. Another widely used tactic is that of scaled sowing of the same crop: often the same seed is sown in up to three temporal intervals, perhaps in three months. Thus if a frost or a hailstorm ruins one or two of the crops another will survive.

Ecological indicators are always observed. These can be catalogues basically into biological and meteorological indicators. Many plants and animals are biologically "hard-wire" programmed for a

[8] I have seen the very patchy effects of very heavy frosts in fields of less than hundred square metres of surface area. In some areas the plants are totally black due to frost burn while others just next to them are quite unaffected. The microclimatic protection from frosts by andenes was made strikingly apparent to me once in Puno when I saw that all of the plants sown within a distance of less than 3m from the terrace wall were quite green after a frosty night, while those a bit further removed were totally black. A straight line running directly parallel to the wall separating the unburned plants from the frosted ones.

tremendous sensitivity to incipient climatic conditions. For instance the wild ducks in the Lake Titicaca region seem to anticipate rises and falls in the surface level of the water. They make their nests higher if they sense a rise in the lever and lower if they sense a fall. Peculiar atmospheric conditions can give rise to some strange visual phenomena, for instance a sort of circular rainbow will sometimes form around the sun which can indicate the onset of a dry spell. However, in line with their emphasis on parallelism people are not satisfied with one or two observations, they observe the behaviour of as many different entities as possible and make a balance of their different predictions to arrive at the best criteria for decision taking. At the local level at least, there are quite effective means employed for quickly arriving at a consensus amongst all affected by the decision. This assures the coordination that agricultural activity requires in the Andean world.

In the following subsections it will be seen how that these considerations lie at the base of the design and use of all Andean agricultural technology and its organised operation. How this is done involves some very complicated procedures that cannot be touched on here. For more details see Araujo 1988, Earls 1991b, 1992, 1996.

The Inca agricultural system is basically a synthesis of techniques, technologies and strategies developed over various millennia by a great number of socio-cultural entities in the different sub areas of the Andean environment. In the above discussion of Winterhalder's work it was shown that irrigation in the highlands, in particular the Western Escarpment, has the basic purpose of attenuation risk due to rainfall and thermal unpredictability by transporting the high altitude pluvial excedent to lower areas. The Valley of Colca has a low and uncertain natural water supply (300-400mm) but counts with a much longer thermally adequate season. The slopes of the middle reaches of this valley are covered with large systems of well made agricultural terraces (referred to as *andenes* in the literature). Before entering directly the theme of Inca agriculture I must briefly outline some of the general patterns of pre-Inca agricultural systems. In part this is because some of these patterns were maintained during the Incanate and continue in use to the present day, and in part because many of the Inca innovations cannot be made clear outside of their historical context.

All the river valley basins of the southwest coast of Peru are characterised by similar large-scale systems of andenes. However, the archaeological studies carried out in the Colca Valley, and well summed up and interpreted by the late John Treacy (1994: 91-111), indicate that the earliest andenes in the valley were cultivated without irrigation. The management of rainfall runoff carried out the water supply[9]. This form of agriculture continued into the period of the region's incorporation into the Wari Empire after the 7th century AD. This early period was characterised by a general alternation between wetter and dryer phases[10] but followed a fairly long relatively humid period that set in between 760 and 1040 AD. It would seem that an agriculture based on runoff management, which involves quite sophisticated water control technology, would have been feasible for drought resistant crops and with a bit more precipitation than the 300 to 400mm of the valley today, though it does seem that the irrigation of andenes and/ or the reconstruction of older ones for irrigation was begun in this period. From 1160 to 1500 AD there was a prolonged dry phase and during this there took place a general transformation to agriculture on irrigated terraces. The Inca occupation then was marked by the intensification of a transformation that was already in progress.

This pattern of agricultural development – i.e. from an earlier stage of terrace agriculture watered by rainfall runoff catchment and management, in early Wari times to a system based on irrigation is paralleled in other parts of Peru. However for most of the Altiplano and the large terrace sculptured systems of the Eastern Escarpment run off water control was never replaced by irrigated andenes except along some of the dryer valley bottoms that seemed to have been of special interest to the

[9] Although much more research is needed it is highly likely that these conclusions apply to the terrace systems of the entire south coast of the Western Escarpment. It is curious that further to the north of Lima there is little terracing of the western valleys. However we have observed some quite well made systems in the interandean valleys of the Callejón de Huaylas in Ancash at Huallpamayo. It is even more curious that these seem to be associated with pottery and architecture that inmediately predated the Wari expansion into the area.

[10] This data is taken from a study of ice cores in the Quelccaya glacier near Cusco. See Thompson, Mosley-Thompson, Bolzan, and Koci 1985.

Incas[11]. It should be noted however that extensive irrigation was employed in the coastal valleys at least a thousand years before it began to be implemented in the highlands. It must not be thought that irrigation was not practiced in the latter because they did not know how to do it. It was just not considered necessary. Farrington (1980) has shown that the technology of Sierra Inca irrigation makes extensive use of supercritical flow in the canals whereas this was not generally done in the coastal systems. As Mitchell (1981) and others have shown, and in line with Winterhalder's argument, highland irrigation is basically with risk control, though in the dryer places nearer the coast there could be no agriculture without it. On the coast both extensive and intensive agriculture is impossible without irrigation. As usual in the Andes no explanation in terms of a single factor is satisfactory. An area that with minimally sufficient rain for agriculture, which makes use of irrigation to attenuate risk, may find that with the onset of dryer conditions agriculture is impossible without it.

On the eastern mountain and valley slopes (the valleys of Sandía in Peru, and of Charazani, Mocomoco and Ambaná in Bolivia (Camino et al 1981; Dollfus et al 1980; Schulte 1996). vast systems of andenes were sculptured onto the landscape for agricultural production but without irrigation. These are worked by a combination of sectorial rotation and rest (*aynoqa, layme, manda*), and water control by a hierarchy of canals. The deepest canals correspond to the watercourses of natural intermittent streams and are artificially walled. The smallest upper canals have courses that are quickly altered by the people working them. In dryer conditions the water is channeled towards the cultivated parcels and when the water is excessive they are redug quickly by hand tools (*rawkana*) to divert the water to the larger drainage canals[12].

## 3.1 Some important Andean agricultural artifacts

Rainwater and other forms of water management were extensively developed in the in the Altiplano in association with other agricultural technologies. I will just mention the two best know examples of these: the ridged fields (*waru waru* in Quechua and *sukka qolla* in Aymara), and the *qocha*[13].

Ridged field agriculture is practiced in many parts of the world. It was used in Denmark in the pre-Viking and Viking periods and is extensively employed today in the high wet tablelands of Papua New Guinea. It was also practiced in many other parts of South America where natural drainage is insufficient or where short but intense wet seasons are followed by long dry seasons. It consists of the digging of drainage canals in strips across the ground and the heaping up of the earth onto the in-between ground to form ridges on top of which the crops are sown. The ridges and canals vary between about one and three metres in width, and the top of the ridge ranges from 80cms to 1.5 m above the canal bottoms. The most systematic study of these is due to archaeologist Clark Erickson (1986; 1987, 1992, 1993). Though these systems are multifunctional I consider their prime function in terms of risk management. The water level of lake Titicaca can vary interannually by as much as a metre so that in seasons of heavy rains when the surface rises and the waters expand up to 200m from the shores, the sown crops are not flooded out. At the same time for lake low water levels the bottoms of the canals are never completely dry and water is retained in the base of the ridge to be slowly pushed moved upwards by capillary action. The origins of these *sukka qolla* systems can at least be traced back some three thousand years to the earliest large-scale ceremonial centres in the circum-Titicaca region of the Altiplano. Erickson however makes a very forceful case that their construction, maintenance and management was the result of the coordination between local groups of agricultors rather than the result of state directed planning[14].

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[11] At this point it should be noted that according to the Aymara population of the area, the current climatic change is bringing about a severe drying out of the lower valley slopes,. This is happening in precisely the same places as where the Incas introduced irrigation during the long dry period that held sway during their political hegemony.

[12] My ongoing research in this area has been supported with the aid of the Rome based NGO Ricerca e Cooperazione and the Pontificie Universidad Católica del Perú. I wish to thank both institutions for their assistance.

[13] This term has no ready translation into English or Spanish, the plural in Quechua is *qochakuna*, so I cannot properly write "*qochas*" to refer to a number of them. The same grammatical considerations apply to the other Quechua and Aymara terms used.

[14] It must be noted that following the incorporation of the Altiplano into the Inca State the ridged fields were abandoned. It seems that the Incas decided that the area was ideal for cammeloid pasturing and that the agricultural requirements could be met from the intensively

The *qocha* are quite different technological systems and are located at quite a distance from the lakeshores. They were first studied by Jorge Flores and Percy Paz (1983) further study was carried out by Rosas (1986) but unlike the ridged fields, their use was never discontinued; they are actively employed to the present day. They consist of geometrically regular concave depressions that have either been dug into the plain or remodeled natural concavities and range from some 20 to 60m across. The sides of the *qocha* are worked into a two or three level radial array of furrows with the crops planted on the smallish ridges in between. The *qocha* are interconnected by complex systems of canals somewhat like a string of beads. The water comes from the runoff of the rains that fall in the higher basin fan that lies behind them. Control of the water levels in the *qocha* is effected by a complex system of dikes and reservoirs that are opened and shut as the conditions demand, and the excess waters are fed into the river and streams that eventually drain into Lake Titicaca. As with the ridged fields these artifacts can best be understood as a system of risk control. Many *qocha* can be used as reservoirs for water storage in dryer periods and for planting when it is wetter. Often the two functions are combined: water is stored in the base while the sides are cultivated. Flores estimates that they also originate in the very distant past, probably to the same epoch as the *sukka qolla*.[15].

## 3.2 The control of vertical space.

It was basically due to anthropologist John Murra that the management of vertical space was first recognised as a fundamental factor underlying Inca and Andean agriculture. With an agricultural altitude range that extends from sea level to nearly 4,400m (in the *punas* of northeastern Bolivia[16]), it is obvious that most crops will only be adapted to a certain altitude range, but it was Murra who related this to organizational forms documented in the Spanish colonial sources (Murra 1964, 1972 1975). He related different organizational practices and crop associations to what he termed "*pisos ecológicos*" (ecological floors or stories) and the Andean strategy of gaining access to a maximum number of these and the products associated with them. Murra has shown how these work in small "duchies[17]" and in the large pre-incaic kingdoms of the Altiplano. *Pisos ecologicos*, particularly in the southern Peruvian – northern Bolivian areas were very often contained in discontinuous territories like islands of an archipelago. The Altiplano-centered Lupaqa kingdom had *pisos* both in the coastal valley and the eastern tropical forest. Recent archaeological work shows that this practice is as old as the formative period of Andean civilizations.

Following on from Murra, Mayer and Fonseca (1979, 1988) have further refined the concept of vertical control with the idea of <u>production zones</u>. Each production zone is characterised by a particular crop association and a technology appropriate for its production, its own administrative system that balances the requirements of communal control and individual preferences; a calendar for the coordination of productive activities; and a system of land tenure (Mayer 1985: 45-84). In many cases the different production zones are separated by walled boundaries, particularly because the annual rotation of the pastoral animals' grazing often places them in one zone while crops are ripening in an adjacent one. While there is a rough correspondence between the *pisos*

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terraced and highly productive valleys to the east of the lake. The Incas also extended the areas of andenes on the surrounding hillsides. The systems lay abandoned for hundreds of years until Erickson began a programme of "applied archaeological" restoration that was so successful that nowadays many NGOs and governmental developmental agencies are involved in their restoration – though unfortunately often without the care that characterised the initial work.

[15] Inge Schjellerup (1986) has described a very interesting structure at Atuén in the Department of Amazonas at an altitude of just over 3,000m. Both ridged fields and andenes depending on the slope like an enormous *qocha* ring this device. Her $C^{14}$ dates as well as aspects of the construction show that the Incas used it but its origins were probably pre-Inca. Besides this she describes other quite distinctive agricultural artifacts in the same general region.

[16] We have registered agricultural at this altitude now, but I must point out that the Aymara peasantry insist that it is a fairly recent development – they often say "when I was a child we only raised cattle up here". So it is likely that viable agricultural activity at this altitude is an adaptation to the recent global warming and does not extend back to the distant past. Even so some authors have stated that agriculture can reach up to 4,300m in this area. This theme awaits further investigation.

[17] I use the word *duchy* as the nearest approximation I can think of for the Spanish term "*señorío*", but both terms are probably not very adequately applied to these particularly Andean political entities.

*ecologicos* and the production zones, due to Andean vertical ecology itself, Fonseca and Mayer (1988) give examples of the splitting of three natural *pisos* into four production zones. The production zones are much more artificial constructs than are the *pisos*.

My interpretation of the archaeological literature (Kolata 1993; Schreiber 1991, 1992; Meddins 1991, Parsons et al 1997) is that the *piso* –style vertical management is much older and for a long period was the basic social pattern of Andean adaptation in the broken and uneven terrain of central Peru. It remained so in most of the more southern circum Titicaca region (but see below). In the 7th century most of this former region was incorporated into the expansive Wari Empire. The Waris made drastic changes in most of the local productive systems, though not in all (Parsons et al 1997), of which the most significant were massive construction of andenes on the valley slopes and irrigation systems. The valley slopes, at least in the Ayacucho region, do not seem to have been cropped in the pre-Wari period, rainfall agriculture was carried out in the flatter up lands of the lower puna (3,800 – 4,000m) and in the wider valley bottoms. These are precisely the areas where European style agricultural systems were later able to establish themselves, as noted in the previous section. Slope agriculture on andenes is perhaps the most fundamental production zone, and its practice entails a similar zoning of the adjacent regions. Thus, I tentatively postulate that the production zone system was basically a Wari innovation. In its later stages the neighbouring southern Tiwanaku State adapted the system in the more uneven valley slopes of its territory – in particular in the previously mentioned valleys of the Eastern Escarpment[18]. However as Murra and others have shown the archipelago style verticality predominated in this whole area.

Agricultural activity in the Andes involves the simultaneous management of a number of parallel calendar cycles. Jurgen Golte (1980) undertook the study of this problem. The activities carried out with the different crop associations in the different production zones need to be highly coordinated so that the necessary activities are carried out in accord with the different stages of the crops' vegetal cycles. This is extremely complicated since even a quite small a political unit may be composed of five or more production zones, each with its particular crop association as well as a technological infrastructure that requires continued maintenance work. In each zone the crops which form an association in any one zone often require attention and labour at different times, while the necessary cropping and pastoral activities in different zones frequently occur at the same time.

On the one hand time and productive planning must be organised in such a way that a maximum number of different activities are combined into a single cycle to avoid the fragmentation of labour time. On the other, the social units engaged in production must be constituted in such a way that they can handle the requirements of simultaneous activities in areas that are can be quite dispersed. Golte proposed that units composed of single household family groups would not be adequate to meet with these conditions. Work carried out by different scholars has verified this proposition (see Araujo 1988; de la Cadena 1986; Earls 1992a, 1992b, 1996, W. Isbell 1996). The fundamental social units are composed of a number of families linked in a complex set of interrelated obligations and mutual reciprocities. While these interrelations are usually phrased in terms of kinship relations, they do not determine them. The organisation of these groups is extremely complex and I cannot discuss it here. While most of the work on this has been carried out in modern Quechua and Aymara communities, it interesting that W. Isbell (1996) has used archaeological evidence to show that this multi-household pattern holds for a variety of Andean socio-cultural configurations including those of Wari, Tiwanaku and the Inca State itself.

It must also be emphasized that the high uncertainty that characterises the highland ecoclimatic environment requires that all planning has to allow for unknowable climatic contingencies. A season which starts out with sufficient rains and adequate temperatures may be broken at any time by a dry spell, if this occurs with clear skies the crops planted are often lost through frosts. Outbreaks of

[18] Above the town of Italaque in the Mocomoco valley of eastern Bolivia we have registered a site with a central rectangular sunken plaza very similar to the great sunken plaza of Kallasasaya in the city of Tiwanaku. The site is situated on top of a round hill with sides encircled by layers of andenes which, together with the site itself, seem to form a single system. At the site we found finely made ceramic shards which, though not diagnostic but taken in the context of the whole structure, suggest that the site formed part of the Tiwanaku polity.

plant diseases are not infrequent and every so many years swarms of locusts, parrots, and other creatures can do away with the crop – or part of it. Recurrent but unpredictable like El Niño happen which either by too much or too little water can devastate a crop. Andean agricultural planning systems must entail the necessity for replanning the agricultural work cycles when such events take place (Earls 1975, 1989, 1991,1992, 1996).

## 3.3 Coordination and slope agriculture.

Effective coordination is a requisite for successful cropping on the steep slopes of the deep Andean valleys. It was noted above that in the southern Ayacucho region the valley slopes were largely uncultivated before their incorporation into the Wari Empire and that European style agriculture never took root in the same areas. The introduction of andenes on these slopes makes for deeper soils, reduces erosion, and gives rise to microclimates that are more stable and risk reducing (my colleague Moshe Inbar will undoubtedly explain these functions with due detail). However, how are we to explain the abandonment of the monumental Inca andenes of the Urubamba Valley slopes? I refer specifically to the extremely "high tech" systems of Pisac and Ollantaytambo. From the available documentary and archaeological evidence we can conclude that these systems were abandoned very soon after the Spanish invasion and their incorporation into colonial *encomiendas* and *repartamientos* (systems for the exploitation of Indian lands and labour). The canals that took water to the terraces were blocked off and the water was funneled straight down to the flatter wider terraces along the riverbanks.

In the first place these terraces were Inca State lands and were worked by specialized agricultors called *yanakunas* recruited from more distant lands under the *mitmaq* system. Following the collapse of the Inca government these specialists rapidly made off to their homelands. The people of the neighbouring local groups never cultivated these lands and made no claim to them[19]. I conclude then that the Spaniards abandoned these andenes because they did not know how to work them and that the neighbouring peoples disclaimed any knowledge of them.

This leads to the following question. What is there about agriculture on fairly steep slopes, even with the rich soils of the Inca andenes, which makes them so difficult to cultivate? The answer lies in the high degree of coordination entailed in their management. Inca andenería was principally employed for maize cultivation[20] and the duration of the maize vegetal cycle, like that of most plants, varies as a function of the temperature. In Table 2 I have listed the altitude ranges and the days from planting to flowering for the varieties of Andean maize gathered from agricultural experimental sites by Grobman, Salhuana and Sevilla (1961)

[19] In 1994 I talked to peasants from the communities of Willoq and Patakancha near Ollantaytambo about this and the general abandonment of the vast agricultural extension programmes that these people attribute to the Incas. They explained that these systems of andenes were never theirs, and distinguished them from the more rustic Late Intermediate terraces that they asserted did belong to their ancestors. When I asked why the Incas never finished all their plans the peasants simply said that "the time ran out on them (the Incas)". Archaeological work by Anna Kendall (1996) bears out this distinction.

[20] Though more food crops were domesticated in the Andes than in any other part of the world I am limiting myself to the discussion of maize cultivation here. Partly because of the very special attention accorded to it on the part of the Inca and earlier Andean states (Murra 1975), and partly because of the limitations of space and time available. I will just mention that in just one Bolivian Aymara community over a hundred clearly distinct potato varieties are cultivated (see also Schulte 1996)

| Variety | Alt.range | D Alt. | Alt. | time.flor | m/day delay |
|---|---|---|---|---|---|
| C.punteagudo* | 2500-3500 | 1000 | 250 | 78 | |
| | | | 2500 | 83.7 | |
| | | | 3000 | 114.7 | 16.129 |
| | | | 3500 | 136.7 | |
| C.puneño* | 3600-3900 | 300 | 3600 | 91 | |
| | | | 3900 | 107 | 18.75 |
| Huayleño* | 2500-3600 | 1100 | 2300 | 87 | |
| | | | 2800 | 135 | 10.416 |
| | | | 3200 | 143 | |
| Morocho* | 2000-3500 | 1500 | 2300 | 104 | |
| | | | 2800 | 149 | 11.111 |
| | | | 3200 | 150 | |
| Huancavelicano* | 2200-3500 | 1300 | 2800 | 121 | |
| | | | 3200 | 140 | 21.052 |
| Rabo de zorro* | 2600-3200 | 600 | 250 | 88 | |
| | | | 2600 | 115 | |
| | | | 3200 | 142 | 22.222 |
| Cusco* | 2400-3300 | 900 | 2800 | 129 | |
| | | | 3200 | 148 | 21.052 |
| Marañon* | 2000-3000 | 1000 | 2800 | 122 | |
| | | | 3200 | 166 | 9.0909 |

Table 2.

Days from sowing to flowering as a function of temperature and altitude for highland maize varieties

The data used has the great limitation of being taken from agricultural stations placed in the untypical flatter environments favoured by western agronomists and the altitudes of the stations probably do not reflect the limits of the altitude ranges optimal for the maize varieties. (for more detailed analysis of these data see Earls 1979, 1989: 359-367, 1991). In the table 2 three columns are used for altitudes. The first, **Alt. Range**, gives the overall altitudes listed by Grobman et al. The second **DAlt**, specifies the altitude range from the subtraction of the first figures. The third, **Alt**, lists the altitudes for which the duration of the vegetal cycle is given. From the latter the altitudes chosen for comparison are those between which the duration of the vegetal cycle shows the steepest change. For example, in the case of Confite Punteagudo the altitude range for which the number of vertical meters required for a one day delay is 3000 – 2500 = 500m. Thus 114.7-83.7 = 31, and 500/31 = 16.129 (last column). Plants sown above or below their optimum temperature-altitude limits are not affected much by changes in their maturation rates. In ideal conditions the maturation rate as a function of temperature follows a logistic curve; the flatter lower and upper sections of the curve corresponding to conditions unfavourable for the plants development cycle (they are susceptible to any form of climatic or biological stress. The altitude lapse rates are calculated from the figures for the most favourable ranges as determined by these constraints. Where only a lower and an upper altitude are given I have used these for the calculation.

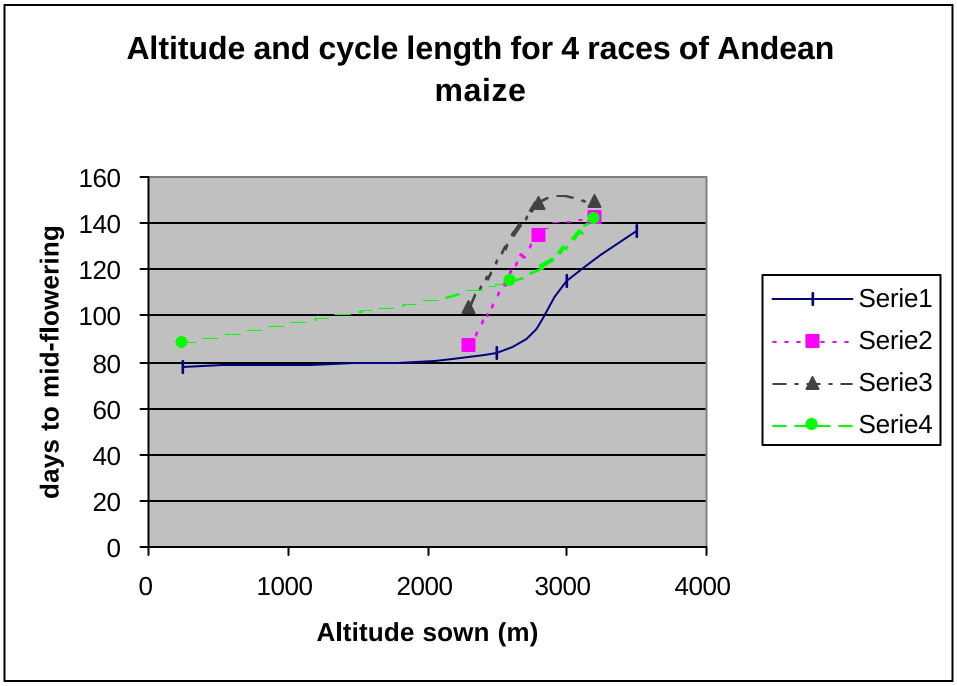


Figure 7

Serie 1 C.*Punteaguda*; Serie 2 *Huayleño*; Serie 3 *Morocho*; Serie 4 *Rabo de zorro*.

In Figure 7 the vegetal cycle to mid flowering are graphed for the four listed maize varieties for which there are more than two altitude/cycle points given. There is only one variety for which 4 points are available. Nevertheless for two races the cycle duration hardly changes for great increases in the inferior altitude range, while for the other two growth rate flattens out above a certain altitude. By visually compounding them an overall sigmoid pattern can be just glimpsed.

For the eight races it is seen that, within this optimum range, there is an average lengthening the maturation time by one day for each 16m of altitude increase[21]. So for an altitude increase of 500m the maturation time increases by one month. This has important implications for the timing of irrigation. Maize plants have certain critical periods. For instance the plants water requirements increase drastically at flowering time, if it does not receive adequate water at this time yield can be reduced by 50-60%.

These characteristics of Andean maize show the importance of highly coordinated relation between the timing of the sowing and other labour activities, and water distribution for successful slope agriculture. The inter-annual temperature variations compound the complexity of the problem. In Ayacucho the mean temperatures for October (the month in which maize is generally sown) differed by 4ºC in 1965 and 1966 (Segovia 1977). If the altitude temperature gradient is translated into ºC then a difference of one degree represents an extension of 9 days in the maturation cycle. Thus four degrees difference represents a difference of 36 days in the duration of the cycle. This thermal uncertainty must also be taken into account in the programming of labour activities. Sporadic early rains also amplify the uncertainty, the soil temperature is lowered changing the initial environment

[21] Ethnographic reports make this figure (16m = 1 day) seem quite conservative. A difference of two months is often mentioned for the duration of the maize cycle at the limits of this altitude range (Camino et al 1981, Mitchell 1981. Among agronomists it is commonly asserted that growth rate for maize doubles for every 6ºC increase in temperature (Frere et al 1975: 213).

for early plant development and hence the whole cycle is prolonged even though later on a dryer period with clear skies can occur which significantly raises both the soil and air temperatures. Sánchez (1971) carried out experiments with maize that show that the length of the vegetal cycle is determined by the climatic conditions obtaining in the first month after planting. This result is consistent with the concern shown by modern peasants with the calculation of most appropriate initial conditions for sowing. While one of the benefits of slope terracing is to reduce the local microclimatic variations (assuming a constant construction pattern and with the same soils) – allowing a people to make linear relation between slope altitude and crop cycle length for agricultural planning – it still remains a very complex decision making process.

In the light of this complexity the rather late development of intensive slope agriculture and the failure of European style agriculture at higher altitudes can be better appreciated. It also helps to explain why the big Andean State systems of Wari and the Incas exerted so much effort into developing appropriate technological infrastructure specifically for slope agriculture. The above data presented for maize, and modern ethnography in indigenous communities (Rosas 1983) suggest that different varieties of maize were consciously acclimatised to the climatically “standardized” conditions obtained in equivalent but spatially dispersed production zones. Such a standardization of climate-to-crop zones would greatly facilitate regional planning but would entail a very careful accounting of time and information processing. There is evidence that the Inca State was actively engaged in this activity.

## 3.4 Time.

By all accounts the Incas seem to have been obsessed with the problem of time. Aveni (19 ) has observed that while the Mesoamerican chronicles hardly mention astronomical activity, the Andean ones are replete with details on the observations that were made of the celestial bodies – at what time of the year and from where they were to be observed. However the native Andean astronomical system is so completely different from those of the ancient Northern Hemisphere states that the Spanish accounts of it were usually quite mistaken[22]. We owe our knowledge of Inca astronomy to the more than 30 years of research that Dutch anthropologist Tom Zuidema (1964, 1980a, 1980b, 1982a, 1982b, 1989a, 1989b, 1990; see also Urton 1981) has dedicated to working it out. In this paper I will not attempt to explain Inca astronomy and the structure of their calendar system. I will only give a brief account of the immense practical importance of temporal synchronization for the Inca State. Zuidema's work on the ceque system of Incaic Cusco has shown this to be a landscape modeling device for the programming of administrative and ceremonial activities and in which the Inca calendar system was embedded. (My colleague Jan Szeminski will have described the basic structure of this in his paper to be delivered here.) One early colonial document (Anon 1906) relates astronomical observations on the ceque system to the timing of irrigation cycles in the major ecological zones around Cusco (see also Earls 1976).

Coordination of agricultural activities on state lands in an empire that stretched over more than 30º of latitude was essential for the maintenance of political and economic stability. The state had to know when, under what circumstances, and to what extent an intervention was needed to redress local and regional disorders arising from the overall situation of high climatic uncertainty with associated crop failures. Unused and under-used lands, usually on the valley slopes, was reclaimed by the state. Large-scale infrastructures were implemented, usually involving the construction of andenes, irrigation systems as well as storage facilities for food. Nevertheless, the widespread belief that the state undertook the job of regulating all agricultural productive activity is quite false,

[22] More recently Jan Szemiñski (1997), following on from Zuidema, but with the eyes of a historian and linguist, has shown that just about everything the Spaniards wrote about Inca history and thought should only be interpreted in the light of the most thorough examination of the Indigenous oral tradition and its expression in colonial documents. His study of the commonly accepted Inca founding figure, Manqu Qhapaq, reveals a complexity of partially intersecting concepts associated with this figure, or complex of figures, that pose important new questions for the understanding of the Inca and Andean past. Such an understanding will in time make it possible to associate conceptual and historical Andean thought with the categories of agro- and socio-technological innovations that become integrated into the specifically Inca agricultural achievement. In this paper I am concentrating on what is common to Andean agriculture, at least since the Middle Horizon, but agricultural innovation was a continual process and has to be thought out, evaluated and realised in social planning. It is hard to imagine that those who brought about important innovations were just smudged out of social memory, even if the way of thinking about these people was completely different to our accustomed “Western historification”.

on the contrary the state preferred to give maximum autonomy to the regional and local systems to regulate their own production. Though in places which the Incas considered vital to their interests they did intervene with a heavy hand. In general though state only insisted that a certain amount of labour time be devoted to the working of state lands, military service, and other tasks. The produce from state lands was used for the feeding of the bureaucracy and for keeping the food stored in the silos at an adequate level. A large part of the state bureaucracy was dedicated to the registering of all relevant information concerning local production and the continual updating of this in the central *quipu* archives in Cusco. The transport of food reserves to regions where the limits of alimentary sufficiency were broken by exceptional climatic or other conditions, and often located a considerable distance from the state silos, involved complicated logistic planning. The food relief had to arrive before hunger gave rise to social and political unrest. This entailed precise timing at every stage. For more detailed analysis of Inca agricultural regulation see Earls: 1975, 1982, and 1989.

## 3.5 Some conclusions on Inca agriculture

The points made above can be summed up in terms of the development of agricultural technologies and social organizations that share the common feature of risk attenuation in the highly uncertain Andean environment discussed in the 2nd section of this paper. The ridged fields of the flatter shores of Lake Titicaca minimise the risk of crop loss due to flooding and drought associated with the substantial fluctuations in the water surface level of the lake. The *qocha* systems make use of rainfall runoff to assure a fairly constant water supply for the crops sown in them by means of complex mechanisms of water catchment and drainage. In the valleys and punas to the East of the Altiplano extensive systems of terracing have been built in which water supply and drainage are controlled by a hierarchy of canals, and worked according to the pattern of sectorial rotation.

The complex vertical ecological system is essentially an artificial construct that developed in stages in the course of Andean history and seems to have been an innovation implemented basically in its present form by the Wari State. Central to this system is the cultivation of maize with irrigated terrace systems on the steep valley slopes. The management of this complex system requires the fine coordination of activities by multiple household units embedded in the social organisation. This basic system was replicated at recursively higher levels to that of the Inca State itself. At each level the system has to be capable of restructuring its organisation in the face of frequently occurring brusque and highly energetic climatic fluctuations. The development of appropriate risk-reducing agricultural technology facilitated this process.

The overall process can be best expressed as one in which a vast number of natural ecosystems was simplified by their artificial replacement by a smaller number of equivalence classes defined by the production zones and articulated in accord to a common basic calendar system embedded in the ceque system. In the final section I will describe the Inca endeavour to replicate a subset of these equivalence classes and the astronomical observations of the ceque system calendar in a single small area with the purpose of further refining the control and regulation[23] of the agricultural system.

## *4. Experimentation and control in the Inca State: Moray.*

There is a well-known theorem in cybernetics due to Conant and Ashby (1970) which states: “Every good regulator of a system must be a good model of that system”. With this in mind and the considerations spelled out at the end of the previous section I set about finding some mechanism

[23] The terms “regulation” and “control” have extremely anathematic connotations in the contemporary world. However here I am using these terms in accord with their cybernetic meanings. In cybernetics both terms are used to designate the mechanisms incorporated in a system that operate to preserve the stability of the system when this is subject to perturbations that occasion instabilities in it. These control mechanisms also function to readjust its internal organisation so that a new configuration of stability can arise when the patterning of external perturbations changes in a consistent manner. This latter function is concerned with the adaptability of the system. Thus, as used here the words have nothing in common with a pattern of centralised interference in local affairs.

that may have served as a model of the agricultural system. In 1975 Father Henrique Urbano and some other friends took me out to the Inca site of Moray. According to the local peasant tradition Moray served as "an Inca agricultural college" and that there are "different climates" on the different terrace levels. Given the exceptional geometric structure of the system I decided that if the Incas were engaged in the replication of equivalence classes of production zones Moray would be the place to carry out experiments to test the idea.

The conditions that had to be met for the system to meet for it to be considered an Inca centre for agricultural experimentation and control were these:

A. Statistically significant microclimatic variation had to be registered on the various terrace levels.

B. The distribution of the microclimates had to be consistent with the geometry of the system and not be attributable to "chance" natural variation

C. Mechanisms had to be identified that allowed the climatic conditions on the terraces to be artificially modified to allow controlled crop experimentation.

D. The system had to incorporate the observation of key dates of the Inca calendar as determined in the Cusco ceque system by Zuidema.

Of course even if the system does comply with these conditions it does not guarantee automatically that the Incas did use it in this way. There are no references to it in the chronicles or other documents that say it was. All that can be said is that could have been used this way and that such a use is consistent with Inca logic. [24]

## 4.1 Site description

Moray is located on a high plateau (3,500m.altitude) about 7 km west of the town of Maras and immediately to the south of the Urubamba River in the Sacred Valley of the Incas, and at some 32km to the northwest of Cusco. It lies at the northern base of a low (4,100m) hill called Wayñunmarka which forma part of a low range separating the plain of Maras from that of Anta further to the south. The site was constructed within a series of natural sinkholes or dolines of various depths cut from the karstic limestone of the plateau out of which four geometrically regular bowl-shaped structures (*muyu*) were formed. The lower flanks of the largest doline, Qechuyoq, are terraced and the remaining parts extensively remodeled. Qechuyoq is over 70m deep but only the lower 28m are terraced. Seven nearly circular terraces within it ring the lower 15m. The higher terraces depart from the circular pattern at the west and south axes, as measured from the centre, and continue around a small artificially flat plain to rejoin the circular patterning at the same points. The other shallower dolines are completely terraced, as are the higher interconnecting areas. None are now cultivated[25]. (Figure 7)

Until about 50 years ago Moray had its own irrigation water supply from an aquifer located in the hill of Wayñunmarka. However this water was diverted to the town of Maras whose own drinking water is very salty. Until then the site was sown with potatoes and barley. The remains of the ancient irrigation system are clearly visible. The water enters the system near the highest part to the south. It follows a series of well defined canals, one of which crosses an aqueduct. The distribution of the water to the terraces in each *muyu* is by means of the typical Inca conduits called *paqcha* , these

[24] The initial stage of this research was funded by the U.S. National Science Foundation (1976). Further work was financed by a grant from the Australian National University to archaeologists Ian Farrington, Ken Heffernan and the author (1985). In 1993-4 I was awarded a Fellowship Guggenheim by the Guggenheim Foundation to research other aspects of the system. I wish to thank these institutes for their support as well as the Australian Embassy in Lima, the Concejo Nacional de Ciencias y Tecnología of Peru, the Universidad de Huamanga, the Centro de Investigaciones de la Universidad del Pacífico, and the Universidad Católica del Perú for smaller awards for data analysis and writing time.

[25] The smallest muyu at the south of the others was abandoned well before its completion. Archaeologist Ken Heffernan of the Australian National University found that a great number of construction tools were dumped in one spot which later became overgrown with weeds. Partially worked stones are scattered around the worked area.

are built in alignment along a single radius as seen from the centres of the *muyu.* The *paqcha* always bring the water to the part of the terrace that are highest, and from here the canals take the water around the base of the terrace walls towards the lowest parts to the north. There are also canals built parallel to these on the border of each terrace for the catchment of any excess water. Though excess water cannot be brought back uphill to each *paqcha* to be fed down to the next level, the natural vegetation at the northern part of Qechuyoq was much denser and various ferns and other plants associated with high humidity only grew in that part. In recent years all this growth has been cleared away by the INC of Cusco which is restoring the appearance of the system for touristic reasons. It is assumed that any excess water was drained downwards inside the andenes at that end of the *muyu*. The locations of the *paqcha* are indicated in figure 8.

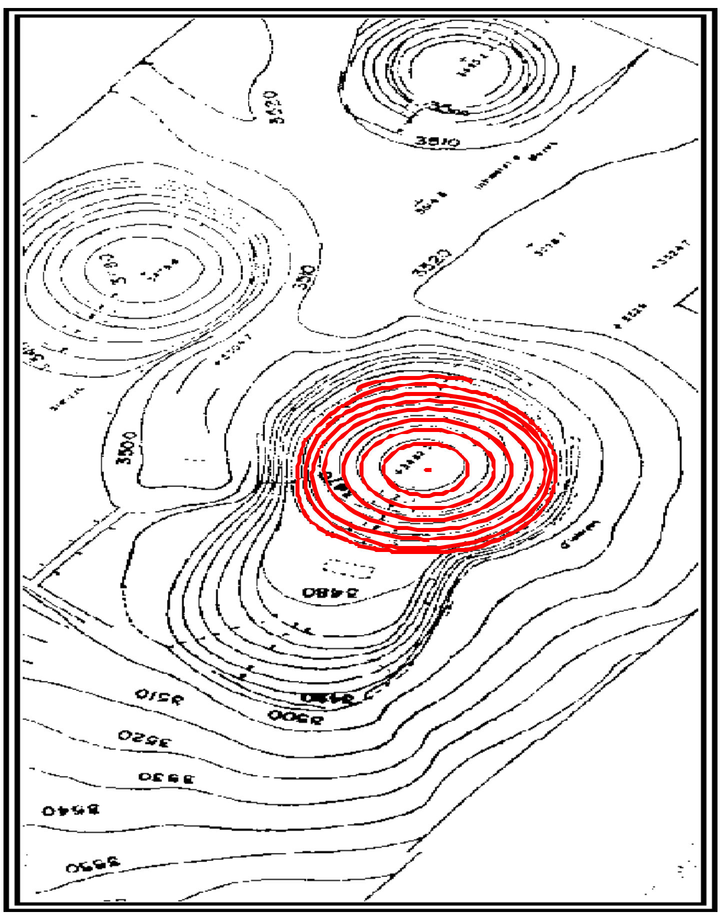


Figure 8.

Ground plan of part of Moray.

## 4.2 Thermal registers and analysis

My initial research was centered on registering soil temperatures and other microclimatic data near the surfaces of the andenes in Qechuyoq along two radii of the system to the west and north of the centre during 12 "Period Days" (PD) over a yearly cycle. Besides being a more important influence on plant life at this altitude than air temperatures, the soil temperatures (at -10cms.) are much more stable than the air temperatures at 150cms, which are always fluctuating because of passing clouds, brief rain showers, etc.. Each PD number refers to the median day of the period of days when observations were registered, PD1 is the 1st of January and PD 365 the 31st of December. When conditions were stable I only down the observations for a couple of days, but when the macroclimate was variable I extended the readings for enough days to be sure that I got a representative sample.

The thermometers were placed at different levels in lines along the west and north axes of Qechuyoq, as measured from the centre point designated 1O. Those along the west axis are labeled 2W, 3W, …,12W, CW (CW refers to the readings taken at the level of the plateau: "Control West")and those of the north 2N, 3N, …12N. Not all positions could be continually controlled however. The soil temperatures were registered through the year on the west axes for “climosites” (CS) 1O, 3W, 5W, 7W, 9W, 12W and. Some of these were only registered for a few months, due to instrument breakage and time delays for getting their replacements, however the CS 1O, 3W, 5W, and 9W were registered throughout the whole year. In the case of the North Axis more andén levels were covered; for each PD. I registered 1O, 3N, 5N, 7N, 9N and 12N only missing a few PD for the reasons stated. See figure 7[26]. On certain occasions I placed all instruments along one or the other axis to better record thermal groupings. When I had more than enough thermometers to cover the basic sites I registered the data for other climosites. Since I could not register the sites simultaneously I have employed lagrangian and statistical interpolation techniques for overall interpretation and adequate presentation.

[26] Ken Heffernan made this map in the survey of the site in the 1985 phase of the work.

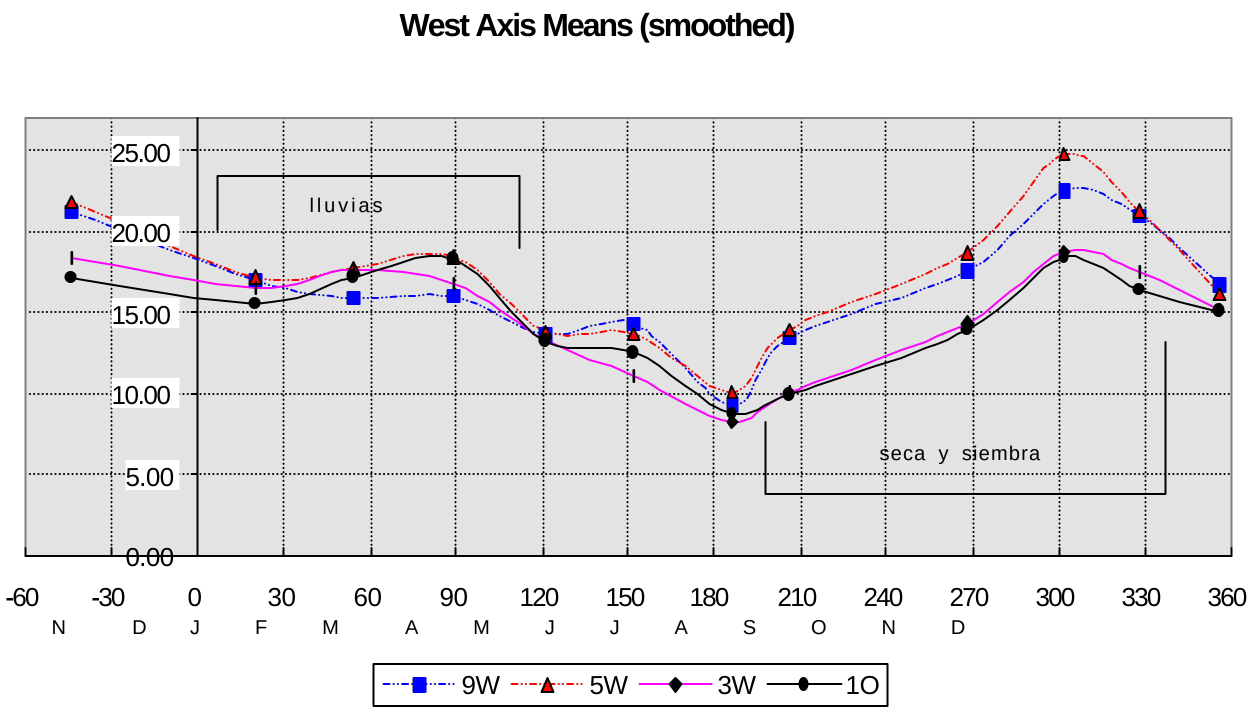


Figure 9.
The wet and sowing seasons are indicated, and the curved are smoothed for easier reading.

As would be expected the period of greatest thermal differentiation corresponds to the sowing season, from August to late November. In the rainy season Dec - Mar and the drying out period that goes on into June the differentiation exists but is much weaker because of the homogenizing effect of the water. The crude data for the four climosites continually registered over the year for the west axis are given in figure 9.

The mathematical analysis of the data revealed a complex thermal structure. The normal lapse rate from centre to rim is not found, instead the system is partitioned into a number of thermal "sectors", each one consisting of four vertically and radial aligned sectors. The lower four levels (Sector I) are generally colder throughout the year and show a smoother diurnal amplitude than the middle four (Sector IIW, levels 5 to 8), or S.IIIW (levels 9 to 12 W). During the sowing season, differences in Ts max of 10ºC occur between the 4th and 5th levels West with daily mean differences of 4 to 5ºC; the curves for S.III.W are similar to those of CS 5W but display no clear patterning.

In figure 10 the only the Ts curves for sectors I and II are displayed are graphed for the day of the zenith solar transit. At this latitude (13’19”) this happens on the 30th of October. The curves are smoothed and 3-point lagrangian interpolation is used to compute the Ts values at hourly intervals. It is interesting is that the S.II.W andenes temperatures are linearly correlated with the width of the corresponding andenes (to a >99% confidence level)

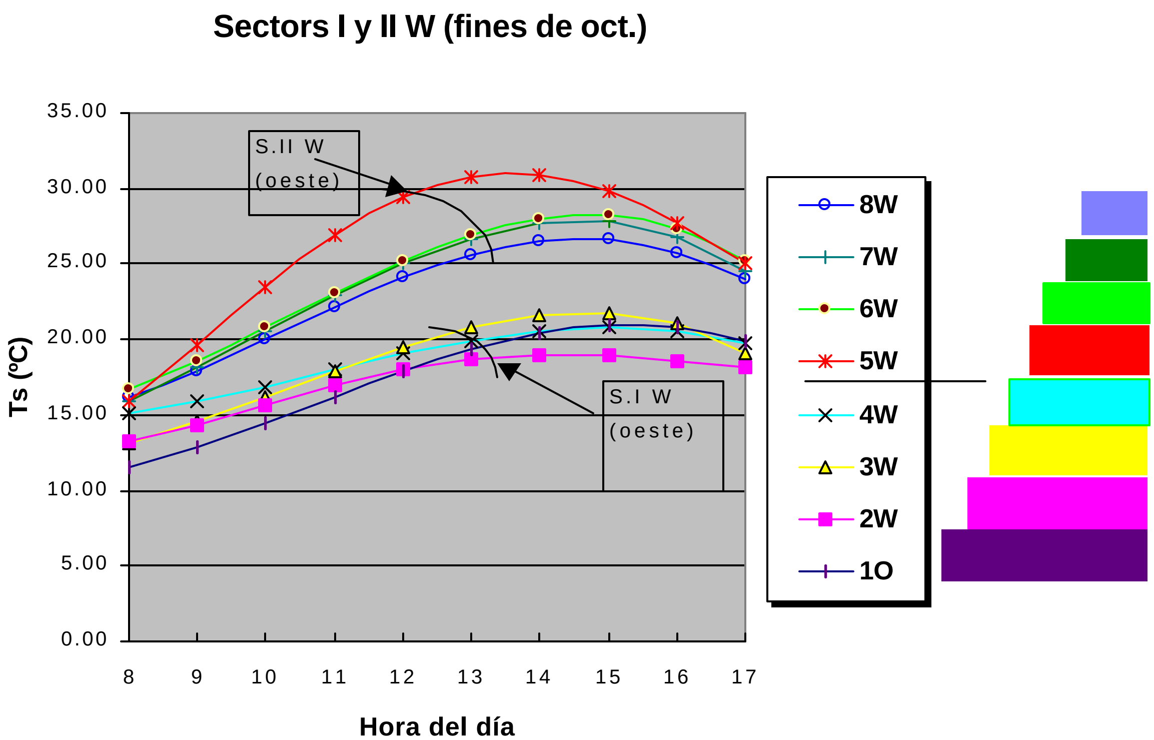


Figure 10.

In figure 11 I have graphed the pairs of sites for corresponding levels on both axes for the mean temperatures. The curve for CS 1O is common to both axes and can be seen to follow a similar path to the pair {3W, 3N}. Equally the annual curves for {5W, 5N} are closely grouped. However the curves {9W, 9N} are similar only for some months while for others close to the winter solstice (21/6) 9N shows a dramatic fall in the average soil temperatures, while 9W follows the same pattern as the others on the same axis.

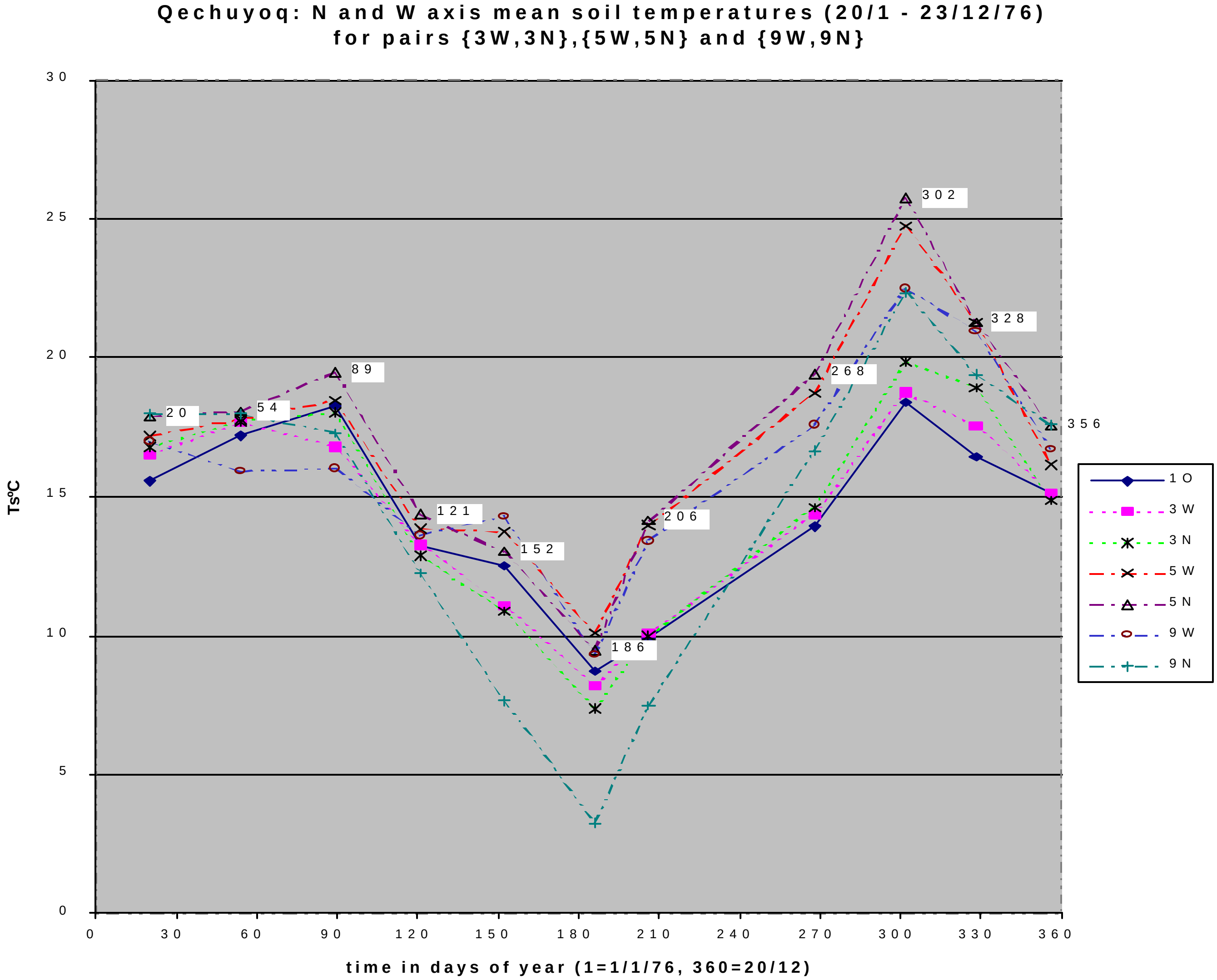


Figure 11

The median PD numbers are indicated in the body of the graph.

From additional measurements made on other levels on the north axis (CS 12N and most of 7N were registered throughout the year) around the period of the solstice I found that the Ts values in S:III N (9 to 12 N) take successively lower values on each ascending terrace. In Figure 12 I have arranged and interpolated from all the data recorded to display the average Ts for all CS on the north axis for the day of the winter solstice.

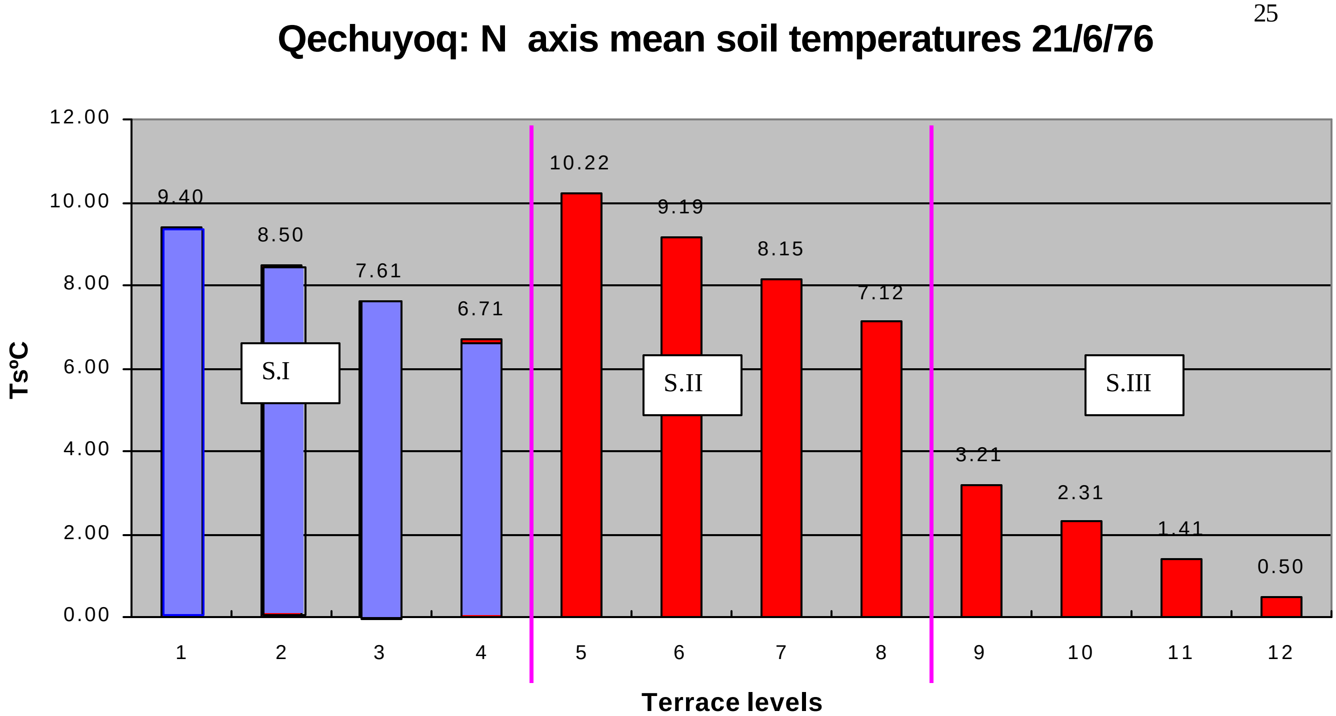


Figure 12.

Distribution of the avg. soil temperatures on the day of the solstice.

On this axis the microclimatic annual sectorization shows up very clearly. In the following surface graph (Figure 13) I used linear and Lagrangian polynomial interpolation to infer the annual Ts trajectories of all levels from 1O to 12N. The graph is probably more reliable than that for the west axis since more data is available and the physical reasons for the S.III N circum-solstice are understood (see Earls 1985, 1989: 153-172). As seen form the upper northern climosites the sun passes below the horizon before and after the 21/6; for each successively higher level this effect lasts longer. At 12 N the soil is completely in the shade for more than a month. The Ts here stays just above 0ºC in this period and then increases rapidly from a daily mean of 4ºC in August to 22ºC in November.

The sector patterning into groups of four terrace levels has interesting parallels with the architecture of the system. To go up or down between the andenes there were built systems of three or four steps made of stones jutting out of the walls (*sayruna*). As is typical for most Inca anden structures these are oriented in opposite directions at each level forming a zigzag pattern. While these are generally built along a straight line seen from the centre, in Qechuyoq the line made by the lower sayruna is broken after 4 levels and those from the 5$^{th}$ upwards follows a different radial line. At the 8$^{th}$ level the anden wall continues around the border of the artificial plain as can be seen in figure 7. While these structural patterns may be coincidental they may also indicate that different work groups were associated with the different sectors. There is other evidence that different work groups were associated with different aspects of the building of the system, and is mostly associated with observable “mistakes”.

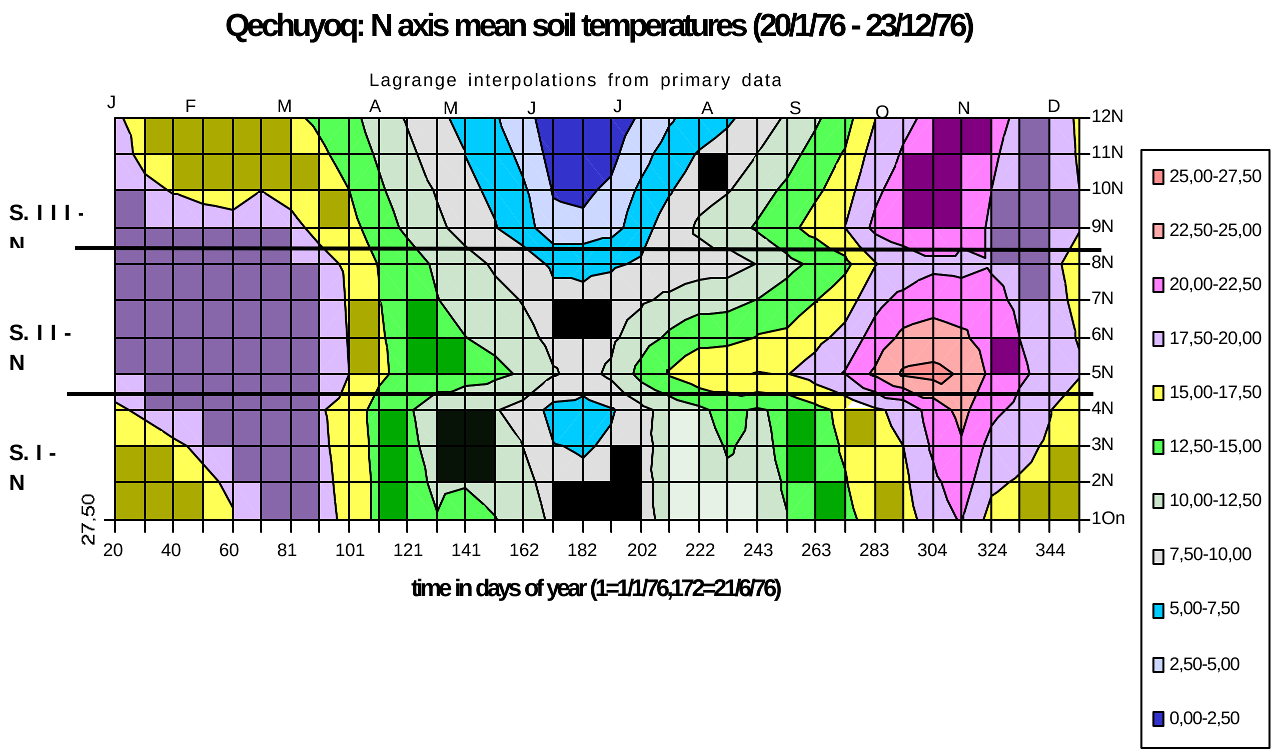


Figure 13

Surface graph of the annual temperature structure on the North Axis.

## 4.5 Possible mechanisms forming the sectors.

I will offer some tentative hypothesis as to the physical causes for the thermal differentiation between the sectors. I have already indicated that the shadow cast by the sun over the northern rim of Qechuyoq during the June solstice period adequately explains the dramatic drop in the soil temperatures for the upper S.III N levels. By the time of the September equinox however the sun has moved sufficiently southwards that the soils of these terraces become as warm as their west axis counterparts. For the other sectors however the explanation is more speculative.

The lowest S.I terraces are cooler than the succeeding S.II levels. Their daily and seasonal thermal oscillations are also more attenuated. This is probably related to the downward flow of any excess irrigation or rainwater. However areas of subterranean water flow can be seen in many parts of the Moray area, as is typical of karstic geological formations, and some of these lead to springs in the slopes down to the Urubamba River. It is possible then that water flows at little depth below the base of the system. This water could work its way upward by capillary action cooling the lower four levels. The study year 1976 was a very average year as regards rain fall, but I have noticed that in other years of much dryer conditions the soil temperatures become less homogeneous with the 3rd and 4th levels heating up much more than the base at 1O . A serious archaeological excavation of the system is needed to determine the reason for the sharp break between the 4th and 5th levels however. Unfortunately the recent restoration project has not included any archaeological study for the understanding of the workings of the machine. Until this is done there is no way of deciding between the many of the plausible speculations for it, including my own, that abound.

The correlation between terrace width and soil temperatures for S.II could be explained by the same physical principles that relate heat, surface temperature, and exposition surface area in passive solar heating receptors. This of course assumes the same humidity for each anden.

## 4.6 A brief note on the astronomy at Moray.

I will not deal here with the details of the astronomical and calendar marking effects that are built into Moray. Suffice to say that sequences of very spectacular visual events are produced in different parts of Moray to mark the day of the winter solstice. The synodic lunar month which precedes the solstice and that which follows it are marked by the onset and conclusion of the shadow touching the tip of an artificial mound[27] next to the 9N climosite, in accord with Zuidema's reconstruction of the Inca calendar for this period. The equinoxes are defined by another shadow that for these dates (22/9 and 21/3) takes a straight line across the terraces passing the centre of Qechuyoq (1.O) and this special mound. (Earls 1989: 129-144. See also the video documentary of the solstice events "*Moray: An Inca agricultural Laboratory*" made by the visual workshop of the Universidad Católica).

The system then complies with the requisite of an in-built real-time control without which it could not have functioned as an agricultural laboratory. Gary Urton (1981a) undertook an extensive of the present day astronomical system and calendar organisation in the community of Misimunay, which borders on Moray. He showed that these are amazingly complex and integrated into every aspect of social, religious and economic life.

## 4.7 Some conclusions and some hypotheses.

Agricultural experimentation is virtually universal in the Andes. In every Indian community there are many people who continually experiment with all plants that come their way in special fields (*chacras*) usually located near their houses, but some do so in a certain *chacra* in every production zone where they have fields. . They watch how different plants "go" under different climatic conditions. How well they resist frost, excessive or deficient rainfall, in hot and cold years, how they behave when exposed to different sicknesses, insects and fungi, etc. A crop's behaviour in a colder year can be simulated by sowing at a higher altitude and in a hotter one by sowing it lower down. A crop's reaction to high rainfall can be tested by sowing it in an area characterised by high rainfall in a "normal year" (if indeed such a term has meaning in the Andean situation) and vice-versa for low rainfall. Simulation and experimentation are routine activities for the native Andean agricultor, so Moray can be seen as simply a systemisation of traditional Andean practice.

My general conclusion then is that Moray was built as an experimental and control centre for the large systems of state andenes built by the Incas on the north side of the Urubmamba River. As mentioned in the previous section these andenes, like Moray, seem to have never been completed. In other publications I have postulated that the slope terraces of Pisac, Ollantaytambo and possibly

[27] This mound is referred to as the *Ñusta* (Princess) by the Quechua inhabitants of the nearby communities and is considered sacred as the daughter of the *Pachamama* (Earth Mother). Important sacrificial offerings made to *Apu* Moray (Lord Moray), who is an important regional deity in himself, take place just below the *Ñusta*. Below Moray the golden palace of the Inka Wayna Qhapaq who is identified with the Sun itself is said to be located.(Earls and Silverblatt 1981)

others in the region were designed with the conscious purpose of producing ecoclimatic equivalence class sectors. Each one reproduced in the sectors of Moray. In the 1993-4 phase of the research I tried to use satelite imaging and ground study to determine if such large-scale sectors could still be identified. However due to the heterogeneity of the vegetation covering resulting from modern attempts to reuse them as well as archaeological projects of restoration, such a patterning could not be detected – if it ever existed. If the most serious (perhaps the only) archaeological project, that conducted by Ann Kendall (1996), is completed for a sizable area then suitable conditions will be created for a new attempt to identify the postulated sectors.

The Moray system would probably have been used for the simulation of all sorts of "might be" climatic conditions and the plants performance established. Plants can be grown in many different sectors and positions such that their lower and upper tolerance limits can be established for different climatic conditions and " standardised" to the corresponding classes by acclimatization. Under dry conditions simply directing excessive irrigation water to crops can simulate heavy rains and floods. Wilting limits can be found by limiting the water and can be tested for the different varieties of maize. Their growth rates established for different soil temperatures. Those sectors that show steep thermal gradients (i.e. S.II W and S.II and III N) could be used to determine growth rates for the different varieties of maize. Moreover, combinations of factors can be studied by varying soil temperatures, insolation and water for plants of interest. It could have also functioned to acclimatize maize and other crops to new ecoclimatic conditions and for the creation of new varieties and sub-varieties[28].

In view of the Inca interest in maize it is important that in a palynographic study carried out in Moray by a Cusco University biology student for his thesis, the only positively identified non wild plant pollen found was that of maize and the *k'antu* flower. The *k'antu* was highly appreciated by the Incas and it is almost always painted on the ceremonial wooden drinking cups (*k'ero*). Since the earliest colonial documents that refer to the area only mention the cultivation of potatoes and introduced barley in the site, and the cultivation of which persisted until the irrigation water was removed, the pollen discovery is consistent with the well documented Inca association of maize with irrigated andenes.

Perhaps the most important conclusion to be drawn from the data and analysis is that the thermal gradient along the two axes is not the normal temperature lapse rate of about -6ºC/1000m. For the terraced 28m of Qechuyoq the mean temperature should decrease by 0.168ºC (assuming that the lapse rate for soil temperatures is the same as that for air temperatures.) In fact in many parts of the system the lapse rate is inverted. It was seen in sections 2 the ground temperatures are more important for plant metabolism at high altitudes than are the air temperatures. In section 3 data was presented showing that the maize vegetal cycle increases at an average of one day per 16m altitude increase, within the range of their effective tolerance limits. This translates into an increase of about nine days for a temperature drop of one degree. It was also pointed out that there is experimental and ethnographic evidence indicating that the average temperature for the month following planting determines the growth rate during the rest of the cycle.

In Moray there are two periods of maximum average temperature differentiation: for S.III N this occurs around the winter solstice but persists through August, the month early sowing. In most of the other sectors the greatest differentiation corresponds to the months for "regular" sowing (September) and late sowing (October and November). In these months average soil temperature differences between adjacent sectors can reach from 3 to 5ºC, and within the S.II sectors of 2 to 3º. These translate back to vegetal cycles differing from a few weeks to more than a month, and to "normal"[29] altitude ranges of many hundreds of meters. In accordance with the general Andean

[28] Frere et al (1975) discuss an interesting experiment made with 4 Bolivian maize varieties in Italy. The much more pronounced seasonal insolation periodicity in Italy had remarkable effects on the plants precocity. Two of the varieties matured much more rapidly and two much more slowly. It is possible that the influence of this could have been tested for by the simultaneous early sowing (August) of the same variety on the upper western and northern terraces with their pronounced different solar exposition rhythms.

[29] In previous publications I have used the term "normal slope" to evaluate lapse rates. A normal slope is an ideal slope of constant gradient and surface conditions, and for which exposition is uniform over an extended altitude range. It is a purely theoretical concept but is useful for comparative purposes (Earls 1989: ***, 1991: ***).

preoccupation with the social requisite of effective coordination for agricultural management it is likely that Moray could have been used as a training ground for optimizing this, at least on state lands.

To finish this section I must point an important limitation of the Moray system for the purposes I have ascribed for it. There are no significant differences between the minimum Ts values for the west axis climosites in any one PD registered. For the north axis only the sites 9N to 12N (S.III N) have significantly different (and lower) Ts minimums for the months before and after the winter solstice. The lower sectors have the same Ts minimums the year round, as do those of the west. In August of 1985 using Lambrecht thermographs I did detect a 3ºC difference for Ts between 1O and 10N in very dry conditions which disappeared in one night of reasonable rainfall. Some measurements made on the south axis did show that the Ts minimums there were 3 to 5º higher than the others in both dry and wet conditions. However my basic point is that frosts are not easily simulated within the system. .

## *5. Some general conclusions on the character of Inca agriculture.*

In the course of this paper it has been seen that Andean agriculture does have a distinctive “special character”. At every scale from the local multifamily and community level to the Inca state, the same problems of poor soils, spatial geoecological diversity, and climatic uncertainty are confronted and managed in basically the same way. Though the details vary greatly at different organizational levels, and for the ethnic groups with diverse environmental homelands and cultural traditions, that are scattered throughout the region, the same basic principles always show through. Risk is attenuated by spatial and temporal task diversification. Spatial heterogeneity is reduced by sophisticated zoning procedures and technological devices, most of which also work to reduce climatic uncertainty. Experimentation, and crop selection and acclimatization are inbuilt features of routine agricultural activity – from the peasant family *chacra* to the Inca State’s Moray. Time is kept by sophisticated astronomical observations that are quite unlike any known in the Northern Hemisphere and which provide the necessary basis for the social coordination required for effective agricultural programming. The complexity of this coordination is such that the nuclear family is a productive unit far to small to for the tasks required and so multiple family units have been at the base of productive activity at least since the consolidation of the Wari Empire.

In computer jargon we could make a metaphorical distinction between western and Andean programming in these terms. Western agricultural planning has much in common with the Von Neumann serial type computer architecture. Multi-tasking can be done, as everyone with a PC knows, but for fairly complex jobs to be carried out (roughly) simultaneously a considerable amount of computing power is required; if not the computer becomes irritatingly slow. Andean job programming has much more in common with the McCulloch inspired parallel architecture of neural computation. Lots of different things have to be taken into account simultaneously and the assessment the whole scene for the decision that is finally taken comes about through an iterated process of shifted weighting of the different factors involved until a coherent picture of the whole emerges. The same job can be done a lot faster and with much less computer power than an equivalent serial machine would require.

The above metaphor is quite useful for appreciating the different character of both agricultural systems. For the same job problem a western engineer is culturally “hard-wired” to look for a solution in terms of higher energy input. The Inca *kamayoq* on the other hand would straight away go to carry out massive consultations among everyone involved until a solution satisfactory to all comes up. He (or she, since certain agricultural administrative domains seem to have been under the control of women) would look for an organizational solution. The recent projects of ridged field restoration of the Peruvian and Bolivian governments make extensive use of tractors to get as much done as quickly as possible, with the result of lots of badly made and unstable fields and lots of disillusioned and cynical Indian peasants. The complete failure of the Green Revolution in the Andes comes as no surprise looked at in this light.

The pressures of the outside world economic order, and particularly so in the recent years of globalization, have weakened the social cohesion of the peasant communities. In the Andean region a greater variety of food plants have been domesticated than in any other part of the world. This incredible biodiversity, also an important feature of the character of Andean agriculture, constitutes the basis for the potential wealth of these countries in a world that is rapidly losing its biodiversity. In recent years this potential is becoming more recognised and much effort is now being put into the recuperation of many crops and varieties that were near the edge of extinction. However the preservation and continued production of these crops is contingent of the preservation of the principles of social organisation that gave rise to them in the first place. With the benefit of the ongoing information and biogenetic revolutions these principles can be easily updated and adequated to the needs of both the Andean peoples and countries, and of the contemporary world in general. That is the primary task for the future.

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Some additional illustrative material I can think of.

1a. Sat. images of Urubamba zone and My. High variety env. Zoom in 2 levels

1b. Aerophoto of My and surroundings. 2 Zoom levels.

1c. The Shippee-Johnson air photo.

1d. Ground Photos of Moray (3 or 4 scenes of the muyus)

s from My doc.

Andean environment: 1 and 2.

Pisac

my from above