Sustaining Agropastoralism on the Bolivian Altiplano: The Case of San José Llanga

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Chapter 03: Ecology and Natural Resources of San Jose Llanga

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Chapter 3

Ecology and natural resources of San José Llanga

Ecología y recursos naturales de San José Llanga

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Summary

In this chapter we report on a broad inventory of natural resources and natural resource dynamics at San José Llanga (SJL). This includes analyses of climate, surficial geology, hydrology, soils and vegetation. Such studies are important because they help us identify key resources that support agropastoral production and the likely sustainability of those resources. In cases where resource use is considered unsustainable, links can be made as to whether activity of humans and livestock, or background effects of climate and geology, are primarily responsible for degradation. Natural resource studies provide a mechanistic basis for understanding risk management behaviour of campesinos and options for increased system productivity.

Secondary information was used in preliminary analyses of climate, based on 43 years of data collected at nearby Patacamaya Experiment Station. Empirical data were used in all other trials and studies, and this information was largely collected in the context of student research projects. Methods included use of transect surveys, soil pits, satellite imagery, preparation of maps using geographical information systems (GIS), chemical analyses of soil, water and forage samples, space-for-time assessments of the successional dynamics of plant communities, and clipping studies to assess seasonal patterns of net primary productivity.

The environment at SJL resembles that of a cold-desert shrubland. The average annual precipitation is 402 mm, with <5% occurring as snow or hail. Considered throughout the year, evapotranspiration is 3.5-times precipitation. The coefficient of variation (CV) for annual precipitation is 23%. The probability that a given year will be markedly drier than average (i.e., with precipitation <75% of the long-term mean) is 0.17. Annual precipitation may have a cyclic character of alternating wetter and drier periods of 11 to 13 years in duration; this was revealed from analysis of seven-year running means. Although there is no long-term statistical trend in annual precipitation, the campesinos perceive that the climate is becoming drier. Seasonality at SJL tends to be defined more by precipitation than temperature, but temperature flux is nonetheless important. Delivery of precipitation is unimodal, with 78% occuring during a five-month period from November to March. This also tends to be the warmest period of the year. This five-month period is when the growing season for crops and native range largely occurs. Crop cultivation is risky, however, due to the variation in rainfall and the occurrence of frost. The cold, dry winter of June through September is a time of ubiquitous moisture stress and prevalence of frost. Native perennial herbaceous plants tend to become dormant at this time. Net primary production and crude protein content of common herbaceous forage begin to drop by June, but this varies by species and site. June and July are the most variable months in terms of precipitation.

The topography of SJL is relatively level, with an overall elevational range of only 61 m (i.e., from 3725 to 3786 m) across 7200 ha. This absence of relief is representative of a large portion of the central Altiplano distant from the footslopes of the Cordilleras. This very modest relief at SJL is still sufficient, however, to underpin several complementary options for resource use by the campesinos. There is a high patch diversity in terms of distinct geomorphic units that vary in edaphic and hydrologic features and degree of salinisation. There are six geomorphic units at SJL, with four important to the agropastoral system. Three of the four important units have been extensively modified by human activity. In general, crop cultivation occurs more on units having non-saline water and soils, while grazing occurs more on units having saline water and soils. The four important units are described below.

An alluvial terrace is located to the west and comprises 25% (or 1800 ha) of SJL. It is elevated by 20 m relative to the rest of SJL. It is a natural formation with gently undulating topography. It is

comprised of non-saline Luvisols and Lixisols. The soil texture and physical position of the terrace is associated with enhanced drainage characteristics (i.e., non-saline ground water is inaccessible to most plants and is located 3 to 10 m below the soil surface). The slight elevation also lends to higher minimum temperatures which mitigate frost risk. The alluvial terrace is the epicenter of rain-fed production of food and forage crops (i.e., potato, *quinoa*, barley) with over 2500 cropping plots in a complex matrix of cultivated (20%) and fallowed (80%) fields. Fallowing may be up to 15 years in duration. Fallowing and the cropping sequence are probably important to help control nematode populations and promote recycling of soil nutrients under the cold, dry ambient conditions. Fallow consists of a couple successional stages. About 25% of fallow fields are in an early successional stage called *kallpas*, which are important for grazing. *Kallpas* have typically been fallowed <4 years and cover varies from near barren, sandy substrates to domination by annual herbs and young, evergreen shrubs such as *thola* (*Parastrephia lepidophylla*). A late successional stage is referred to as *tholares* and is dominated by associations of large *thola* and bunch grasses such as *Festuca orthophylla*. *Tholares* are used for grazing, but also for harvesting fuel wood from mature *thola*. The *kallpas* initially appeared to be subject to significant wind erosion, but our studies revealed that topsoil is redistributed among *kallpas* and adjacent *tholares* plots. This fortuitous situation may be related to plot size and intermixing of *kallpas* and *tholares* that creates a suitable matrix for recapture of wind-blown soil. The campesinos commonly report perceptions that crop production on the alluvial terrace is declining, but we have no hard evidence to support this contention. If crop production is indeed declining we speculate that several factors could be contributors. The best hypothesis is a lower annual rainfall associated with a dry phase in the postulated rainfall cycle. Other hypotheses include altered cultivation practices such as substitution of chemical fertilisers for manure or expanded use of tractor tillage. Substitution of chemical fertilisers for manure may save labour, but with a cost of declining soil organic matter. Tractor tillage could be contributing to soil erosion by disturbing the *kallpas/ tholares* matrix.

The second unit is an alluvial fan, which is centrally located near the main settlement of SJL and comprises 15% (or 1080 ha) of the study area. This low-lying unit was created when campesinos re-directed the channel of the *Khora Jahuíra* River some 15 years ago, and is in a slow process of expansion. This highly productive unit is comprised of non-saline, medium-textured Fluvisols. Non-saline ground water occurs at a depth of 2 to 3 m below the soil surface, accessible to roots of alfalfa (*Medicago sativa*), an important perennial forage crop. The alluvial fan receives annual additions of fresh water and sediment from periodic flooding of this ephemeral, rain-fed river. Depositional processes give the fan a slight convex shape. By virtue of its use in cultivated forage production (alfalfa and barley) under flood irrigation, the alluvial fan is the critical backbone of local smallholder dairying and the production of improved sheep breeds. One risk, however, is the danger posed for crop damage due to the occasional large flood and late-season frosts.

The third unit is the deltaic deposits, located to the east, which comprises 10% (or 720 ha) of SJL. This low-lying unit is made up of slightly saline Solonchak soils. The water table occurs at 1.6 to 2.4 m below the soil surface, but the water has a moderate level of salinity and is therefore marginal for crop sub-irrigation. This unit has also been modified by humans over the past decade in that irrigation water is supplied via a 23-km canal from the saline Desaguadero River, which originates from Lake Titicaca. Alfalfa, barley, *quinoa* and potatoes are grown here under a variety of flood-irrigated and rain-fed conditions. The deltaic deposits have allowed some aspects of livestock production to expand. This contribution appears unsustainable, however, in that irrigation water from the Desaguadero River may eventually salinise crop fields and limit cultivation.

Finally, the fourth and largest unit is the fluvio-lacustrine plain, which comprises 38% of SJL (or 2736 ha) and occupies most of the remaining landscape. It is about 12 km in length along its east to west axis. Formerly a lake bed, this unit incorporates the lowest elevations in the study area. It is typically used for grazing. Compared to the other units it has been relatively free of overt modification by people, although evidence of low earthen ridges (possibly used years ago for water spreading or delineation of grazing areas) are evident in some locales. Vegetation is dominated by perennial grasses or halophytic "cushion plants," depending on location. Seasonal productivity of herbaceous communities may be more constrained by frost occurrence or salinity rather than lack of soil moisture, especially in instances where plant roots have easy access to ground water. Soils vary from hyper-saline Solonchaks (about 1061 ha or 39% of the fluvio-lacustrine plain) and moderately saline Solonchaks (1079 ha or 39%) to slightly saline Solonchaks (386 ha or 14%) and non-saline, fine-textured Fluvisols (210 ha or 8%). The fluvio-lacustrine plain is subtended by a very high water table from 0.6 to 1.5 m beneath the soil surface. Water is found in a honeycomb of often discrete and relatively small cells and varies greatly in salt content. Proliferation of hand-dug wells may ultimately help homogenise ground water. Landscape position, soil type, and to a lesser extent grazing pressure, appear to influence plant community composition on the fluvio-lacustrine plain. A grazing gradient occurs by virtue of settlements (and hence livestock corrals) being located at the western end of the fluvio-lacustrine plain. Barren zones occur in the centre. Barren zones may be saline, but it has been hypothesised that the widespread denudation is probably most related to effects of seasonal flooding. The hyper-saline Solonchaks (termed *eriales* with afloramiento salino) often appear barren except for communities of small, halophytic cushion plants of very marginal forage value (referred to as *q'auchiales* and *q'otales* in the local vernacular). Dominant species of cushion plants include *Salicornia pulvinat*a (an obligatory halophyte) and *Anthobrium triandru*m. The moderately saline Solonchaks are dominated by 280 ha of barren land (*eriales*), 450 ha of communities dominated by a tall-statured, valuable forage named *Hordeum muticum* (*yawarales*), and 350 ha of communities dominated by prostrate, low-growing forages such as *Distichlis* and *Muhlenbergia* spp. with some *H. muticum* (collectively termed *gramadales*). The *gramadales* tend to have forages of moderate feeding value and lower productivity (3.8 t DM/ha) which are commonly grazed to a high intensity; this is often due to proximity of *gramadales* to sacrifice zones of heavy livestock use near corrals. *Distichlis* tends to naturally dominate *gramadales* if salinity is higher. If salinity is lower we speculate that grazing can shift community composition from a dominance by *Hordeum* sp. to dominance by *Distichlis* and *Muhlenbergia* spp. The latter case occurs in only a small portion of the fluvio-lacustrine plain, and our view is that when *Distichlis* dominates moderately saline *gramadales*, this represents a stable, but degraded, rangeland state in relation to animal production. This is one of the few notable instances where we suspect grazing to have altered plant community composition at SJL in recent times. Non-saline soils are relatively rare on the fluvio-lacustrine plain, but the plant communities on non-saline soils tend to be more productive than those on saline soils. Fine-textured fluvisols (300 ha) support communities dominated by tall-statured *Festuca dolichopylla* (termed *chilliwares*, with a productivity of 7.6 t DM/ha) and *Calamagrostis curvula* (*p'horkeales* with a productivity of 7.9 t DM/ha); the latter sites under heavy grazing appear to have increased representation of *C. curvula* relative to *H. muticum* and others. Finally, there was evidence from studies of plant population distributions and salinity of soil and water that the hyper-saline zone has increased relative to the moderately saline zone on the fluvio-lacustrine plain in recent times. Young cohorts of *S. pulvinata* have spread into moribund stands of other species less tolerant of high salinity, this population shift appears to be correlated with sharp changes in salinity of top soil and ground water. While the extent of expansion of the hyper-saline zone may be pervasive, it could not be quantified due to the heterogenous patchiness of the central fluvio-lacustrine plain. Several hypotheses could explain migrating ecotones, but our results are interpreted to suggest that increasing salinity of patches is related to erosion of the uppermost layer of sandy/loam soil. This exposes a subtending layer of highly saline clay and silt, probably deposited when the site was repeatedly inundated as an endoreic lake. The exposed saline layer then presents a more hospitable environment for species such as *S. pulvinata.*

In conclusion, SJL exhibits signs of environmental degradation, but attention to geomorphic units and associated land use is critical in understanding degradative processes. The character of SJL is fundamentally defined by its landscape position and role as a recipient for water, soil and salt at a macro-scale.

Although the fluvio-lacustrine plains appear denuded to the casual observer as a result of contemporary over-grazing, <20% are degraded in this manner. This equates to <8% of the cantón overall. These *gramadales* and *p'horkeales* sites in sacrifice zones near settlements show altered species composition and conform to equilibrial theory for plant/herbivore interactions. In contrast, however, the vast majority of acreage on the fluvio-lacustrine plains has been denuded by flooding and salinisation. This situation conforms to non-equilibrial theory where abiotic factors overwhelm management. A mix of controls, even within geomorphic units, is thus evident. This limits generalisations regarding system-level designations of equilibrial or non-equilibrial behaviour.

Contemporary threats to sustainable resource use may occur more in the farming dimension of this system rather than the grazing dimension. The best example of human-induced degradation is the recent irrigation of the deltaic deposits with saline water. Mis-management of topsoils on the alluvial terrace remains to be verified. The people have positively affected their farming environment, however, by creating the alluvial fan.

Resumen

En este capítulo se presenta un inventario general de los recursos naturales y de su dinámica para San José Llanga. Se incluye análisis del clima, geomorfología, hidrología, suelos y vegetación. Estos estudios son importantes por que ayudan a identificar recursos claves que apoyan la producción de los sistemas agropastoriles y elaborar sobre su sostenibilidad. En casos donde el uso de los recursos se considera insostenible, referencias pueden hacerse sobre si la actividad humana y del ganado ó si los efectos subyacentes del clima y la geología son los responsables primarios de la degradación. Los estudios de los recursos naturales proporcionan los mecanismos básicos para comprender las estrategias de manejo del riesgo por los campesinos y de las opciones para incrementar la producción del sistema.

Para el análisis del clima se usó información secundaria, el análisis se basó en 43 años de datos colectados en la cercana Estación Experimental de Patacamaya. En todos los otros ensayos y estudios se usaron datos empíricos, los que fueron mayormente tomados en el contexto de proyectos de investigación de estudiantes. Los métodos incluyen: el uso de transectos de estudios, excavaciones para la descripción de perfiles de suelo, imágenes de satélite, preparación de mapas usando Sistemas Geográficos de Información (SGI), análisis químico de muestras de suelo, agua y forraje, sustitución de tiempo por espacio para determinaciones de la dinámica de la sucesión vegetal de las comunidades vegetales, y estudios de corte de fitomasa para determinar los patrones estaciónales de la productividad neta primaria.

El medioambiente de SJL recuerda el de los arbustales de desiertos fríos. La precipitación anual en SJL es de 402 mm, con <5% en forma de nieve o granizo. Considerando el periodo de un año, la evapotranspiración es 3.5 veces mayor que la precipitación. El coeficiente de variación (CV) para la precipitación anual es de 22%. La probabilidad de que un determinado año podrá ser marcadamente más seco que el promedio (p.e. con una precipitación <75% de la media) es 0.17. La precipitación anual podría tener un comportamiento cíclico con periodos alternados secos y húmedos desde 11 hasta 13 años de duración; como se evidencia del análisis de 7 años de desviaciones acumulativas anuales. Influencias de las oscilaciones de "El Niño" (ENSO) podrían tener un rol determinando los patrones cíclicos de precipitación. Aunque no se detectaron tendencias estadísticamente significativas para la precipitación anual en el largo plazo, la percepción de los campesinos es que el clima está volviéndose más seco. En SJL, las estaciones tienden a ser definidas más por la precipitación que por las variaciones de la temperatura, pero los cambios de temperatura no dejan de ser importantes. La forma de la precipitación es unimodal, con 78% de ocurrencia en un periodo de cinco meses entre Noviembre y Marzo. Este periodo tiende a ser también el periodo del año con temperaturas más elevadas. Este periodo de cinco meses es la época en el que mayormente ocurre el crecimiento de las plantas tanto cultivadas como las de los campos naturales de pastoreo. Sin embargo, la agricultura es riesgosa, debido a la variación en la precipitación pluvial y la ocurrencia de heladas. El frío y seco invierno desde Junio hasta Septiembre es un período donde el déficit de humedad y prevalecía de helada es infaltable. Las plantas herbáceas nativas tienden a entrar en dormáncia durante este período; la producción primaria y el contenido de proteína cruda de las plantas forrajeras herbáceas comunes empiezan a disminuir en Junio, aunque estos cambios pueden variar por especie y sitio. Junio y Julio son los meses más variables en términos de precipitación.

La topografía de SJL es relativamente plana, con un rango altitudinal general de solo 61 m (p.e., desde 3.725 hasta 3.786 m) a través de 7.200 ha. Esta ausencia de relieve es representativa de una amplia región del Altiplano central, alejada de los piedemontes de las Cordilleras. Este muy modesto relieve en SJL, sin embargo, es todavía suficiente para que los campesinos desarrollen varias opciones complementarias de uso de los recursos. Se presenta una alta diversidad espacial manifestada en las distintas unidades geomorfológicas que varían en términos de sus características edáficas, hidrológicas y grado de salinización. En SJL se identifican seis unidades

geomorfológicas, siendo cuatro las más importantes para el sistema agropastoril. Tres de estas cuatro unidades han sido ampliamente modificadas por la actividad humana. En general, los cultivos son más comunes en las unidades que disponen de agua y suelos no salinos, mientras que el pastoreo, es más común en las unidades que tienen agua y suelo salinos. Las cuatro unidades importantes se describen a continuación.

La *terraza aluvial* está localizada al oeste de la comunidad y abarca un 25% (ó 1.800 ha) de SJL, se encuentra 20 metros más alta con relación a las otras unidades de SJL. La terraza aluvial es una formación natural de topografía ondulante. Está formada por Luvisoles y Lixisoles no salinos. La textura del suelo y la ubicación física de esta terraza está asociada con características de buen drenaje (p.e., el agua subterránea no salina se encuentra entre 3 a 10 metros de profundidad y es inaccesible para la mayoría de las plantas). La escasa elevación también tiende a una mayor temperatura mínima, lo que mitiga el riesgo de helada. La terraza aluvial es el epicentro de la producción agrícola y de forrajes a secano (p.e. papa, *quinua* y cebada) en cerca de 2.500 parcelas de cultivo distribuidas en una compleja matriz que incluye parcelas actualmente con cultivos (20%) y en descanso (80%). El descanso puede ser hasta de 15 años, debido en parte al clima severo, y presenta un par de estados sucesionales. Cerca del 25% están en estados iniciales de sucesión y se las denomina localmente *kallpas*, estas *kallpas* típicamente están en descanso por <4 años y la cobertura vegetal varia de casi totalmente descubierta con exposición del substrato arenoso hasta dominio de hierbas anuales y arbustos jóvenes siempre verdes tal como la *thola (Parastrephia lepidophylla)*. Las *kallpas* son importantes para pastoreo. Los estados sucesionales tardíos, referidos a nosotros como *tholares* y que están dominados por asociaciones de *tholas* grandes y pastos tufosos, mayormente de *iru ichu (Festuca orthophylla)* son usados para pastoreo, pero también para extracción de leña de las plantas adultas de *thola*. Las *kallpas* al inicio del periodo de descanso, durante la época seca, aparentan estar bajo fuerte erosión por el viento, pero nuestros estudios indican que el suelo superficial estaría siendo redistribuido entre las *kallpas* y los *tholares* adyacentes. Esta situación fortuita puede estar relacionada con el tamaño de la parcela y la mezcla de *kallpas* y *tholares* que crean una matriz apropiada para la captura del suelo transportado por el viento. La percepción general entre los campesinos es que la producción de las parcelas de cultivo en la terraza aluvial está decreciendo; pero nosotros no tenemos suficiente evidencia para confirmar esta controversia. Si la producción de cultivos estuviese evidentemente disminuyendo, especulamos que varios factores podrían estar contribuyendo para que ésto ocurra. La mejor hipótesis es la disminución de la precipitación anual asociada a la fase seca del postulado ciclo de la precipitación. Otras hipótesis incluyen alteraciones en las practicas de cultivo tales como la sustitución del uso del estiércol por fertilizante químico o el incremento del uso del tractor. La substitución de estiércol por fertilizante químico puede ahorrar trabajo, pero al costo de perdida de materia orgánica del suelo. La preparación de suelos con tractor podría contribuir para la erosión del suelo debido a la alteración de la matriz *kallpas/tholares.*

La segunda unidad es el *abanico aluvial*, el que se localiza en el centro cerca de las viviendas y comprende el 15% (ó 1.080 ha) del área de estudio. Esta unidad está ubicada en la zona baja de la comunidad y fue formada cuando los campesinos cambiaron la dirección del cause del río *Khora Jahuíra* hace más o menos 15 años. Esta unidad está en un proceso lento de expansión. Esta unidad altamente productiva está conformada por suelos Fluvisoles no salinos de textura media. La napa freática se encuentra entre 2 y 3 m debajo de la superficie del suelo y es accesible para las raíces de la alfalfa (*Medicago sativa)* que se ha convertido en un importante cultivo forrajero perenne en la zona. El abanico aluvial recibe contribuciones anuales de agua fresca y sedimentos por inundaciones periódicas de este río con caudal efímero alimentado por el agua de lluvia. El proceso de deposición de sedimentos da a la llanura una forma ligeramente convexa. Debido a su uso para producción de forraje (alfalfa y cebada) con riego por inundación, la llanura aluvial constituye un componente crítico para los pequeños productores de leche y para la producción de ovejas mejoradas. Un riesgo en esta unidad, sin embargo, es el peligro que existe de daño para los cultivos debido a inundaciones severas y heladas tardías.

La tercera unidad es la de los *depósitos délticos* y está localizada al este del territorio de la comunidad. Esta unidad abarca un 10% (ó 720 ha) de SJL. Esta unidad se encuentra en la parte baja y los suelos son Solonchak ligeramente salinos. La napa freática se encuentra entre 1.6 y

2.4 m debajo de la superficie del suelo, pero el agua tiene un moderado nivel de salinidad y es por lo tanto marginal para el riego de cultivos. Esta unidad a sido también modificada por intervención humana en la última década por la construcción de un canal de riego de 23 km de largo para transportar agua salina desde el Río Desaguadero, este río se origina en el Lago Titicaca. Bajo una variedad de condiciones de riego por inundación o a secano se cultiva alfalfa, *quinua* y cebada. Los *depósitos délticos* han permitido la expansión de algunos aspectos de la producción animal. Esta contribución parece inestable, sin embargo, debido a que el riego con agua del Río Desaguadero puede eventualmente salinizar las parcelas agrícolas y limitar su cultivo.

Finalmente, la cuarta y más extensa unidad es la llanura fluvio-lacustre, la que abarca el 38% (ó 2.736 ha) y ocupa la mayor parte del área remanente de SJL. De este a oeste tiene un largo de 12 km. Originalmente un lecho de lago, esta unidad incluye las cotas más bajas del área de estudio. Es típicamente usada para pastoreo. Comparada con las otras unidades, la llanura fluvio-lacustre ha estado relativamente libre de modificaciones antrópicas, aunque, evidencias de antiguas barreras de tierra (posiblemente usadas para distribución de agua y/o delimitación de áreas de pastoreo todavía existen en algunos lugares) están presentes en algunos lugares. La vegetación dependiendo del sitio que se trate es dominada por pastos perennes ó plantas halófilas en cojín. La producción estacional de las comunidades de herbáceas podría estar limitada mas por las heladas o salinidad que por la falta de humedad en el suelo, especialmente en situaciones donde las raíces de las plantas tienen fácil acceso al agua subterránea. Los suelos varían desde Solonchaks hiper-salinos (1.079 ha ó 39 %) hasta Solonchaks moderadamente salinos (386 ha ó 14%) y Fluvisoles no salinos de textura fina (210 ha ó 8%). La llanura fluvio-lacustre esta condicionada por una napa freática muy superficial (p.e., desde 0.6 hasta 1.5 m). El agua subsuperficial no es continua y se presenta en forma de una red de depósitos que recuerdan un panel de abejas, relativamente pequeños y que varían en contenido de sales. La proliferación de la construcción manual de pozos podría ultimadamente favorecer la homogeneización del agua subterránea. La ubicación en el paisaje, el tipo de suelo y en menor medida la presión de pastoreo parece que influyen la composición botánica de la comunidad de plantas de la llanura fluvio-lacustre. En esta unidad se presenta una gradiente de pastoreo, atribuida a los patrones de uso del suelo (y por lo tanto incluye corrales de ganado), localizados en el extremo oeste de la planicie. Areas sin vegetación se presentan en la parte central de la planicie. Las áreas descubiertas de vegetación pueden ser salinas, pero nuestra hipótesis fue que la presencia abundante de áreas descubiertas está probablemente mas relacionadas a efectos de inundaciones estaciónales. Los suelos Solonchak hiper-salinos (llamados *eriales* ó afloramiento salino) parecen frecuentemente descubiertos excepto por comunidades de pequeñas plantas de halófilas acojinadas de valor forrajero marginal (referidos a nosotros como *q'auchales y q'otales* en el idioma vernácular); especies dominantes de plantas en cojín incluyen *Salicornia pulvinanata* (una halófila obligada) y *Anthobrium triandrum*. Los Solonchacks moderadamente salinos están dominados por 280 ha de suelos descubiertos de vegetación (eriales), otras 450 ha de comunidades vegetales están dominadas por el valioso pasto de mediano tamaño llamado *Hordeum muticum* (*yawarales*), y 350 ha de comunidades están dominadas por pastos cespitosos de corto crecimiento tales como *Distichilis* y *Muhlenbergia* spp. con alguna presencia de *H. muticum* (colectivamente llamados *gramadales*). Los gramadales tienden a tener forrajes de moderado valor alimenticio y de baja productividad (3.8 t/MS/ha) los cuales son generalmente pastoreados con altos niveles de intensidad; esta alta intensidad de pastoreo esta frecuentemente relacionada a la proximidad de los *gramadales* a las zonas de sacrificio bajo uso intensivo del ganado, cerca de los corrales. El *Distichilis* sp. tiende naturalmente a dominar en los gramadales si la salinidad es alta. Si la salinidad es baja nosotros creemos que el pastoreo puede cambiar la composición de la comunidad vegetal de dominada por *Hordeum muticum* a dominada por *Distichilis* y *Muhlenbergia* spp. El último caso se presenta sólo en una pequeña parte de la planicie fluvio-lacustre, y nuestra interpretación es que cuando *Distichilis* domina en gramadales moderadamente salinos, representa un estable, pero degradado estado del campo natural de pastoreo, con relación a la producción animal. Esta es una de las pocos instancias notables donde pensamos que el pastoreo habría alterado la composición de la comunidad de plantas en SJL en tiempos recientes. Suelos no-salinos son relativamente raros en la planicie fluvio-lacustre, pero las comunidades de plantas en suelos no-salinos tienden a ser más productivas que las de en suelos salinos. Los Fluvisoles de textura fina (300 ha) presentan comunidades dominadas por pastos altos de *Festuca dolichophylla* (llamados *chilliwares*, con una productividad de 7.6 t/MS/ha) y *Calamagrostis curvula* (*p'orkeales*, con una productividad de 7.9 t/MS/ha); en estos últimos sitios parecería que bajo pastoreo pesado *C. curvula* incremento su representación con relación a *H. muticum* y otras plantas. Finalmente, sobre la base de estudios de distribución de plantas con relación a la salinidad de suelos y de aguas se encontró evidencia de que la zona hiper-salina recientemente se incrementó con relación a la zona con salinidad moderada en la planicie fluvio-lacustre; ésto se evidencia por el incremento de cohortes de plantas jóvenes de *S. pulvinanata* en medio de grupos de plantas moribundas de otras especies menos tolerantes a altos niveles de salinidad y ésto está correlacionado con cambios bruscos de la salinidad del suelo y del agua superficial. A pesar de que se cree que el grado de expansión de la zona hiper-salina pueda ser constante, ésto no pudo ser cuantificado debido a la extrema heterogeneidad de las manchas en la planicie fluvio-lacustre central. Varias hipótesis podrían explicar la migración de ecotonos, pero nuestros resultados son interpretados para sugerir que el incremento de la salinidad de las manchas estaría relacionada a la erosión de la capa de suelo superficial areno/francoso. Esto expone una capa inmediatamente inferior de arcilla y limo altamente salina, probablemente resultado de depósitos cuando el sitio fue repetidamente inundado debido a su condición de lago endorreico. La capa salina expuesta presenta, un medio ambiente más favorable para especies tales como *S. pulvinata*.

En conclusión, SJL exhibe signos de degradación ambiental, pero es crítico prestar atención a las unidades geomorfológicas y al asociado uso de la tierra para comprender estos procesos de degradación. El carácter de SJL esta fundamentalmente definido por su posición en el paisaje y su rol como receptor de agua, suelo y sales a una escala macro.

Aunque, la llanura fluvio-lacustre aparenta estar descubierta de vegetación al observador casual, como resultado del sobre-pastoreo contemporáneo, sólo <20% está degradada de esta manera. Esto equivale a <8% de todo el cantón. Los *gramadales* y *p'horkeales* en las zonas de sacrificio cerca de las viviendas muestran una composición de especies alterada y se ajustan a la teoría de equilibrio para las interacciones planta/ herbívoro. Al contrario, sin embargo, la mayor parte de la llanura fluvio-lacustre la vegetación ha sido eliminada por inundación y salinización. Esta situación sigue la teoría de desequilibrio donde los factores abióticos se sobreponen a los de manejo. Una mezcla de controles, por lo tanto, es evidente, incluso dentro de las unidades geomorfológicas. Esto limita generalizaciones en relación con especificaciones de sí el nivel del sistema tiene un comportamiento en equilibrio o en desequilibrio.

Peligros contemporáneos al uso sostenible de los recursos pueden ocurrir más en la dimensión agrícola de este sistema que en la dimensión de ganadería. El mejor ejemplo de degradación inducida por humanos es la reciente irrigación de los depósitos délticos con agua salada. El manejo inapropiado del suelo superficial en la terraza aluvial permanece aun sin verificar. La gente, sin embargo, ha afectado positivamente su medioambiente agrícola a través de la formación del abanico aluvial.

3.1 Introduction

Development and change in traditional societies is strongly affected by interactions between humans and their natural environments. Management practices used by most low-input, rural societies represent an amalgamation of technologies, social rules and organisational structures that have been tested over time and found suitable for sustainable exploitation of resources. In many cases, however, changes in population, social values, market opportunities, government policies or technology alter a delicate balance between humans and sustainable resource use. Given these critical relationships, a thorough knowledge of the biophysical environment is essential to comprehend and attempt to improve low-input production systems such as SJL.

Our overall purpose in this chapter is to characterise the environment and natural resources of the Cantón of SJL. This is accomplished in two steps. First the climate, surficial geology, hydrology, soils and vegetation are described. Descriptions include brief accounts of land use (i.e., cultivation, grazing, fuel wood collection, etc.) for broadly defined geomorphic units. Second, an analysis is presented concerning selected aspects of ecosystem dynamics at various spatial and temporal scales.

All of the analyses listed above set the framework for us to begin to address some of the broad ecological questions posed in the original SR-CRSP proposal, namely: What is the status of the semi-arid environment that supports a representative agropastoral system on the central Altiplano? Is degradation evident and, if so, which landscape components are most vulnerable and why? What is the role of people and livestock in environmental degradation? Are natural processes (i.e., drought or salinisation) more important than humans and livestock in determining environmental trends? The reader should consult Chapter 1 (*Project objectives and research approach*) for a review of these and related questions.

Before delving into the details of natural resources, it is first important to note the degree to which the Cantón of SJL is an open or closed system. This helps define the boundaries of the system in an ecological sense. The answer, however, depends on which resource is considered. For example, SJL is largely a closed system with respect to grazing resources. The 5600 head of livestock that reside in SJL (see Chapter 5: *The grazing livestock of San José Llanga*) are confined within the borders of the cantón, even during severe drought. During drought the stocking rate at SJL is reduced through animal sales rather than through increased dispersal of animals that has been observed elsewhere when societies are poorly served by markets (see Chapter 6: *Household socioeconomic diversity and coping response to a drought year at San José Llanga*). Reciprocal rights of regional grazing access such as those common among neighbouring pastoralists in Africa (Solomon Bekure et al 1991; Coppock 1994) are therefore absent here at the level of the cantón. In terms of access to river water, SJL is an open system because some of the rivers affecting resources within the cantón originate elsewhere and are subject to other demands upstream (see Section 2.3.1: *Regional highlights of physical geography and environment*). For cultivation, a number of key inputs such as chemical fertilisers and mechanised power for tillage come from outside the SJL system. Livestock manure has traditionally been a key component of the agropastoral system due to its use as a crop fertiliser. Manure, however, has been commonly exported out of SJL in recent years and thus increasingly serves as a cash crop (see Chapter 4: *Household economy and community dynamics at San José Llanga*).

3.2 Methods

3.2.1 Climate and description of natural resources

Material in this chapter primarily draws upon thesis work completed by eight Bolivian undergraduates and one American master's student (see Section 3.5: *Literature cited* and Chapter 1: *Project objectives and research approach*). Thesis work was targeted to address specific topics which would contribute to an overall understanding of the structure and function of the SJL agropastoral system. Such studies were variously conceived, designed and supervised by resident scientists of the SR-CRSP with ancillary guidance and participation by Bolivian co-investigators and U.S.-based principal investigators. General methods for major studies concerning climate and descriptions of natural resources and their dynamics are given below.

Researchers of the SR-CRSP relied mostly on secondary data to describe climate at SJL. This included attributes such as frost risk, evapotranspiration (ETp) and air temperature (i.e., daily maxima and minima). Secondary climate data were collected at the nearby Patacamaya Experiment Station with standard descriptive statistics prepared by INTECSA (1993) and SENAMHI (1994). The community of SJL does not have a climate station. The Patacamaya Experiment Station is located 17 km north of the main barrio of SJL at an elevation of 3789 m slightly higher than SJL at 3725-3786 m. Original work was performed by the joint IBTA/SR-CRSP project to evaluate whether precipitation data collected at the Patacamaya Experiment Station were representative for SJL. Peña (1994) examined several decades of corrected rainfall data and concluded they were reliable and representative. Standard statistics for annual and monthly average precipitation (and variability) are presented here for the period 1951-93. A seven-year running mean was used to evaluate possible cyclic behaviour of annual precipitation; this method has been used elsewhere to detect climate patterns (Kolata 1993). Peña (1994) performed other interpolation methods to evaluate precipitation data, including an appraisal of data from Sica Sica, another community located 23 km to the east of SJL at an elevation of 3820 m. Interested readers should consult Peña (1994) for a review of this work.

Miranda (1995) mapped and characterised the landscape and soils throughout SJL according to standard procedures established by USDA (1951). Panchromatic aerial photos (scaled at 1:20 000) were examined in the laboratory with a stereoscope. Broad geomorphic units were delineated for 100% of the study area. Geomorphic units were defined by topographic features and indicate situations where predominant soils share a common genesis. After this preliminary stratification according to geomorphology, transects were walked across geomorphic units and soil samples were collected using a soil auger. These transects covered about 81% of the study area; only a locale north of the *Khora Jahuír*a River was unsurveyed for soil features (Miranda 1995). Variation in soil morphology, topography, drainage and vegetation were noted at sample points along transects. Based on this information soils were then grouped into soil units as defined by the revised legend in FAO/UNESCO/ISRIC (1988). For each soil unit at least three pits were excavated in representative locations. Soil profiles were described and sampled by genetic horizon. Soil samples from at least one profile per unit were analyzed by a commercial laboratory for organic matter, available phosphorus (P), cation exchange capacity (CEC), electrical conductivity (EC) of a 1:5 soil extract, pH, particle-size distribution and exchangeable cations. Soil analysis methods were standard. For example, soil texture was determined using the pipette method. Organic matter was determined using the method of Walkley and Black (1934). Electrical conductivity is a measure of salinity and involved use of a conductivity meter. The conductivity value for the 1:5 extract was corrected using a regression equation relating the electrical conductivity of the saturation extract (ECe) and the EC of the 1:5 suspension. The regression equation was derived from laboratory measurements. A general review of pertinent analytical methods for soils is provided in chapter 2 of Cook and Stubbendieck (1986).

Treadwell and Liebermann (1992) produced a vegetation map of SJL at a scale of 1:20 000. This map was produced using data from recent (1992) aerial photos and field surveys and covered 90% of the study area. The final map identified 27 vegetation associations crudely differentiated in terms of relative cover of dominant species. Most associations had adequate plant cover to allow categorisation, but two were virtually denuded. Treadwell and Liebermann (1992) referred to these denuded sites as either *eriales* (barren and hypersaline) or afloramiento salino (i.e., patches where salts have precipitated on the surface from capillary action of ground water). These two site types together comprised <1% of the area of SJL. The 27 associations identified by Treadwell and Liebermann (1992) were further characterised by Massy (1994) in terms of plant species cover and peak standing biomass. For the purposes of this chapter, however, much of the detail contained in the final 1:20 000 vegetation map of Treadwell and Lieberman (1992) with additional information from Massy (1994) was deemed unnecessary. The 27 associations were first consolidated into six aggregates. Another five types were added to account for cultivated crops and rain-fed fallow, giving a final total of 11. This simpler schema is more in line with land-classification schemes used by the local campesinos (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). Other detailed information on seasonal land use for grazing is presented in Chapter 5: *The grazing livestock of San José Llanga*.

Peña (1994) performed an extensive survey of water resources at SJL. He measured depth and elevation of the water table at 137 and 40 points, respectively, and determined water quality at 19 other locations which were systematically selected. Of the 15 chemical parameters measured by Peña (1994), electrical conductivity (ECw) is most pertinent to this chapter because it gives values indicative of the salinity of water. The survey did not include analysis of ground water resources for the far western portion (about 25%) of SJL because the depth to the water table there could not be measured with available equipment. This was largely the geomorphic unit referred to later in this chapter as the alluvial terrace.

3.2.2 Dynamics of natural resources

Our studies of ecosystem dynamics examined phenomena at various spatial and temporal scales. For example, we examined seasonal and annual changes in photosynthetic activity of rangeland vegetation, plant community and population dynamics in fallow fields that occur over a span of 15 years, and spatial shifts of ecotone borders (i.e., boundaries of different associations of range vegetation) that probably occur over decades. Because of funding limitations and the relatively short period of field research, the longer-term ecological dynamics commonly had to be assessed using indirect (non-observational) methods. These methods included, for example, space-for-time substitution [see chapter 3 in Cook and Stubbendieck (1986)] and interviews of campesinos who had managed the land for many years. In some instances studies were strategically focused on tell-tale manifestations of ecosystem change. Conclusions based on such work can be risky, but in our case there was little choice if the main research questions were to be addressed. In addition, work in this chapter occasionally refers to several preliminary studies that were often lacking in statistical rigour, but still yielded potentially important insights. Methods for studies of natural resource dynamics are briefly described below.

The primary objective of work by Washington-Allen (1994) was to describe how the landscape (i.e., plant communities, cover types) of SJL changed according to season and year and to generate hypotheses as to cause(s) of change. One aspect of these studies was to describe annual dynamics of landscape change using four remotely sensed images covering the period 1972-87. Three images were from the Landsat Multispectral Scanner (MSS; 1972, 1986 and 1987) and one was a Thematic Mapper satellite image (TM; 1984). The 15-year period included the year 1983-4, generally regarded as a time of severe drought. In 1983-4 annual precipitation was 43% of the long-term annual mean, while growing season precipitation was 33% of the long-term mean (Painter 1992; this chapter). Another aspect of research was to describe seasonal dynamics of plant cover in a year having a near-average level of precipitation. Six Landsat MSS images were used for the period of August, 1986, to September, 1987, a time when annual precipitation actually tended to be higher than the long-term mean. The response variable in all analyses was the transformed normalised difference vegetation index (TNDVI), an indicator of vegetation biomass and cover that relies on detection of intensity of greenness, which in turn is an indicator of photosynthetic activity. The validity of using TNDVI is reviewed in Washington-Allen (1994, 8-9). A geographical information system (GIS) was used to produce maps of the study area for dominant plant communities and land use (i.e., largely grazing versus cultivation). Values of TNDVI were then tracked for various site types as a means of quantifying and tracking stability and resilience of green vegetation under perturbation due to precipitation dynamics, both on an inter-annual and seasonal basis.

Seasonal changes in standing crop biomass and plant productivity on the rangelands of SJL were the foci of a pilot study by Prieto and Yazman (1995). The seasonal patterns of range forage production are important in evaluating the productive potential of plant communities and stocking strategies. Prieto and Yazman (1995) set up livestock-proof exclosures made of sheep fencing and wooden posts to protect 16-m^2 plots in each of three vegetation associations at SJL. These associations were important for grazing and were variously dominated by perennial *Calamagrostis*, *Festuca* or *Distichlis/Muhlenbergia* spp. Prieto and Yazman (1995) estimated above-ground standing crop for eight months (i.e., January to August) of 1995. This period included the growing season and most of the subsequent dry season. For each exclosure they clipped three, 0.5-m^2 quadrats to ground level each month. Standing biomass was hand-separated and weighed on an oven-dried basis (i.e., 48 h at 65°C). The three quadrat subsamples were randomly selected within each exclosure; previously harvested quadrats were avoided. Estimates of aboveground net primary production (ANPP) in g/m^2/day were obtained by difference on a monthly basis for the growing season. This was done using mean weights across the three subsamples in a given exclosure on a given date in comparison with values from adjacent months. The design used by Prieto and Yazman (1995) lacked replication for associations. The results, however, have utility for this synthesis chapter.

Seasonal change in the nutrient content of forages is important in terms of understanding constraints for range animal production. It has been typically found, for example, that range plants are highest in nutritive value during and shortly after wet periods in rangeland systems. Once plants mature and a system dries out, however, plants can rapidly decline in nutritive value (Van Soest 1994). Characterisation of forage nutritive dynamics was conducted by Lopéz (1994). She collected approximately 180 samples of grass, forb and shrub materials during 1992-3. These materials were hand-plucked in an attempt to mimic bites taken by sheep, cattle and donkeys throughout the Cantón of SJL. Lopéz (1994) conducted a variety of chemical analyses on forages but here we present only her results for crude protein (CP) content, quantified using the micro-kjeldahl method (AOAC 1980). Crude protein is a general measure of plant nitrogen content because it incorporates both protein and non-protein sources of nitrogen. Crude protein, however, is a commonly accepted means to assess forage value (Van Soest 1994). Here CP content was averaged for 14-15 samples per month to provide a graphical presentation of seasonal trends.

Ecological dynamics and successional trends for cultivated lands are important in understanding structure and function of the SJL system. Traditionally, campesinos of the central Altiplano have used extended fallow periods of up to 15 years to allow crop plots to recover fertility and soil structure under constraints of low precipitation and cold temperatures (see Section 2.3.2: *Regional historical highlights*). The extended fallow is also used to reduce density of parasitic nematodes, which cause serious depredation of potato crops in the Andes (Dollfus 1982). As will be shown, cultivated lands comprise up to 50 % of SJL and provide the vast majority of calories for the campesinos each year (see Section 4.3.3: *Household production system*). Cáceres (1994) used a space-for-time method in which she characterised vegetation in 20 cultivated fields fallowed from one to six (or more) years. She collected data on plant density and cover using the PCQ (or Point-Centered-Quarter) method [chapter 3 in Cook and Stubbendieck (1986)]. Her sampling design included four replications for each age class of fallow, but this was ultimately found to be inadequate for statistical analysis. The general findings from the cover data of Cáceres (1994) are referred to here, however, because they provide a broad indication of vegetation change in fallow over time. Surveys of the succession of perennial plant species on fallow fields by Queiroz et al (1994) are also highlighted. The ecology of fallow fields was addressed in the most detail by Barrera (1994), who studied changes in species composition of perennial plants in fields that also had been under fallow for different periods. He based his selection of fields on interviews with land owners. He also scaled his sampling with respect to the changing heterogeneity in each age class of fallow by using a larger plot size (i.e., 40 m^2) for younger fields fallowed <4 years and larger types of plants, and a smaller plot size (i.e., 20 m^2) for all older fields having a less variable plant cover. Six plots were randomly located in every field; numbers of shrubs and large bunch grasses were counted throughout each sample plot. Plots were subsampled to estimate abundance of physically smaller taxa. For medium-sized species half of the plot was used. Three 0.25-m^2 quadrats were systematically placed inside plots to enumerate the smallest plant species (Queiroz et al 1994).

When a visitor comes to the cultivated fields of SJL on a windy day during the dry season, a distinct impression is that much of the sandy topsoil is being lost to wind erosion (Dr. D.L. Coppock, IBTA/SR-CRSP, personal observation). In particular the younger fallow fields in the cropland matrix appear most vulnerable to soil loss because they appear to lack sufficient perennial vegetation to hold soil in place. The campesinos do not seem to have intercrops to serve as windbreaks, or any another obvious form of landscape modification, that minimises effects of wind erosion. If soil losses to wind erosion are significant, it could greatly affect sustainability of the whole agropastoral system. Barrera (1994) therefore also investigated the possibility that fallow fields were subject to high net losses of top soil due to wind erosion. He randomly placed vertical rods in the soil of five fallow fields (ranging from two to six years of age) and measured changes in soil depth around each rod for several consecutive months in the dry season of 1993. Change in soil volume per plot was estimated using change in soil depth and approximations for bulk density of soil.

Vegetation associations identified by Treadwell and Liebermann (1992) were sometimes very distinct in terms of abrupt changes at their borders, or sometimes one association would gradually change into another across a great distance. In either case the transition zone between two or more types can be referred to as an ecotonal gradient or ecotone (Odum 1971, 157-9). Given the importance of understanding which factors allow one plant association to invade the domain of another, along with the need to gauge dynamics of salinity in the system (see Section 2.3.1.1: *Regional physical geography and soils*), an analysis of abrupt ecotones at SJL was undertaken by Garabito (1995). He focused on plant associations in the salt-affected rangelands, which comprise about 40% of the Cantón of SJL. One question he wanted to address was: Are salt-tolerant associations expanding in the area, and, if so, could this be attributable to a gradual increase in salinisation? This is an important question because plant associations tolerant of highly saline conditions are undesirable in terms of grazing value compared to vegetation under conditions of moderate to low salinity (Chapter 5: *The grazing livestock of San José Llanga*). Garabito (1995) categorised ecotones into seven types based on pairings of adjacent vegetation. For each type of ecotone he located three examples. Along transects he then systematically selected sample points and measured attributes of plants [i.e., cover and plant size of certain taxa like salt-tolerant cushion plants (e.g., *Salicornia pulvinata* and *Anthobrium triandrum*)], ground water (electrical conductivity) and soil (electrical conductivity, pH and depth). In this case he wanted to see if the cushion plants were expanding their influence and, if so, whether or not this expansion was associated with increasing salinisation.

3.3 Results and discussion

The location and physiographic setting of the Cantón of SJL (7200 ha in size) has been previously reviewed. See Section 2.4.1 (*Local environment*) for these details and a description of the semi-arid puna of the central Altiplano within which the Cantón of SJL is found.

3.3.1 Climate

3.3.1.1 Precipitation

Using various interpolation methods, Peña (1994) concluded that the mean annual precipitation at SJL is about 402 mm. Less than 5% of the annual total occurs as snow or hail; snow or hail is most likely in the months of June, July and August. This mean annual total of 402 mm is very close to that for the Patacamaya Experiment Station (i.e., 406 mm; see Table 3.1). Based largely on work by Peña (1994), we believe measurements at Patacamaya Experiment Station to be reasonably accurate estimates of the true values for climatic parameters at SJL.

Overall, the climate of SJL is representative of a cold, dry ecosystem. Influences of elevation and physical geography have dictated these climatic attributes (see Section 2.2.1: *National highlights of physical geography and environment*). A large proportion of the world's arid and semi-arid ecosystems fall into the general category represented by SJL and the semi-arid puna of Bolivia. Perhaps best described by the inclusive term "cold-desert shrubland," homologues for this extensive, semi-arid puna of South America can also be found in the Great Basin of North America and in central, northern and southwestern Asia (Stoddart et al 1975). The following discussion reviews several important aspects of climate at SJL in isolation. This is followed by an integrated presentation relevant for understanding seasonal constraints on crop cultivation and plant growth.

As is typical of arid and semi-arid systems world-wide, precipitation at SJL is seasonal. The overall pattern at SJL is a uni-modal delivery of precipitation, as 93% (or 379 mm) of annual precipitation occurs throughout eight months (September to April) with 78% (or 313 mm) concentrated across the five months regarded as the growing season for crop cultivation (November to March). Accordingly, there is a distinct dry season which is commonly four months in duration (May to August) when only 7% of total annual precipitation is received (Table 3.1). Precipitation is most variable in the wet-to-dry and dry-to-wet transition periods. October is the second most variable month for precipitation in the dry-to-wet transition period; this is illustrated in Figure 3.1. That October is highly variable in terms of precipitation is emphasised here for two reasons: (1) October is a time of critical decisions by campesinos concerning field preparations for the up-coming cropping season (Section 4.3.3: *Household production system*), and (2) October is a time when grazing livestock are likely to be in the poorest condition, and therefore most in need of a flush of nutritious, green forage stimulated by early precipitation once temperatures begin to warm-up (Chapter 5: *The grazing livestock of San José Llanga*).

The high aridity at SJL is illustrated by the fact that mean potential evapotranspiration (ETp) exceeds precipitation by nearly 3.5-fold for the entire year. On a monthly basis ETp ranges from 20-times the precipitation in July to 1.25-times the precipitation in January (Table 3.1). This implies that plants dependent on precipitation are typically under threat of moisture stress, but that this markedly varies by month.

Annual precipitation at SJL is dynamic. Since 1951 to the present there have been two years with an annual precipitation between 200 and 225 mm, while there have been four years when precipitation has exceeded 550 mm (Figure 3.2). For the 42 years of data collection overall, the coefficient of variation (CV) for annual precipitation is 23%. This figure is markedly lower than the 45 to 50% range for CVs associated with tropical, arid rangeland systems in Australia (Caughley et al 1987) or South Turkana, Kenya (Ellis 1992), where rainfall varies from 200 to 350 mm per annum. Caughley et al (1987) noted that if an ecosystem has a CV for annual precipitation >30%, it is likely to be characterised more by non-equilibrial dynamics of consumers and plants and better defined in accordance with its variability rather than by long-term means. According to these precipitation criteria, the SJL system therefore seems to reside more on the equilibrial side of the rangeland spectrum. This conclusion would be strengthened further if evapotranspiration demand was incorporated, since this greatly influences effectiveness of precipitation. For example, if the higher evapotranspiration demands of hot, arid Australia or

Table 3.1. *Monthly dynamics of key climate variables for the Patacamaya Experiment Station, 1952-92.* Sources: INTECSA (1993) and SENAMHI (1994).

	Month												
Variable[1]	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Annual[2]
Precipitation (mm)	4.1	9.6	25.2	19.9	30.2	66.6	102.4	67.1	50.1	17.8	7.8	5.5	406.3
ETp (mm)	78	109	127	142	148	145	128	120	128	101	81	73	1380
Mean Temp. (°C)	5.1	6.5	8.8	10.8	12.1	12.3	12.2	12.0	11.6	10.2	7.3	5.1	9.5
Mean Max. Temp. (°C)	15.8	16.8	18.0	20.2	21.1	20.2	19.4	19.2	19.1	18.8	17.3	15.7	18.5
Mean Min. Temp. (°C)	-5.9	-3.8	-0.5	1.4	3.0	4.4	4.8	4.7	4.1	1.3	-2.9	-5.5	0.4
Mean Frost Days	28.3	25.5	15.2	9.7	4.2	1.5	0.7	0.4	1.5	10.4	24.1	27.8	149.2
Probability of Frost	1.00	1.00	0.88	0.88	0.70	0.33	0.21	0.30	0.47	0.85	1.00	1.00	0.72

[1]Where ETp is evapotranspiration, frost days are days when frost occurs, and the probability of frost was calculated over a 30 to 31-day period per month.

[2]Annual values for precipitation, ETp and mean frost days are totals while the others are means.

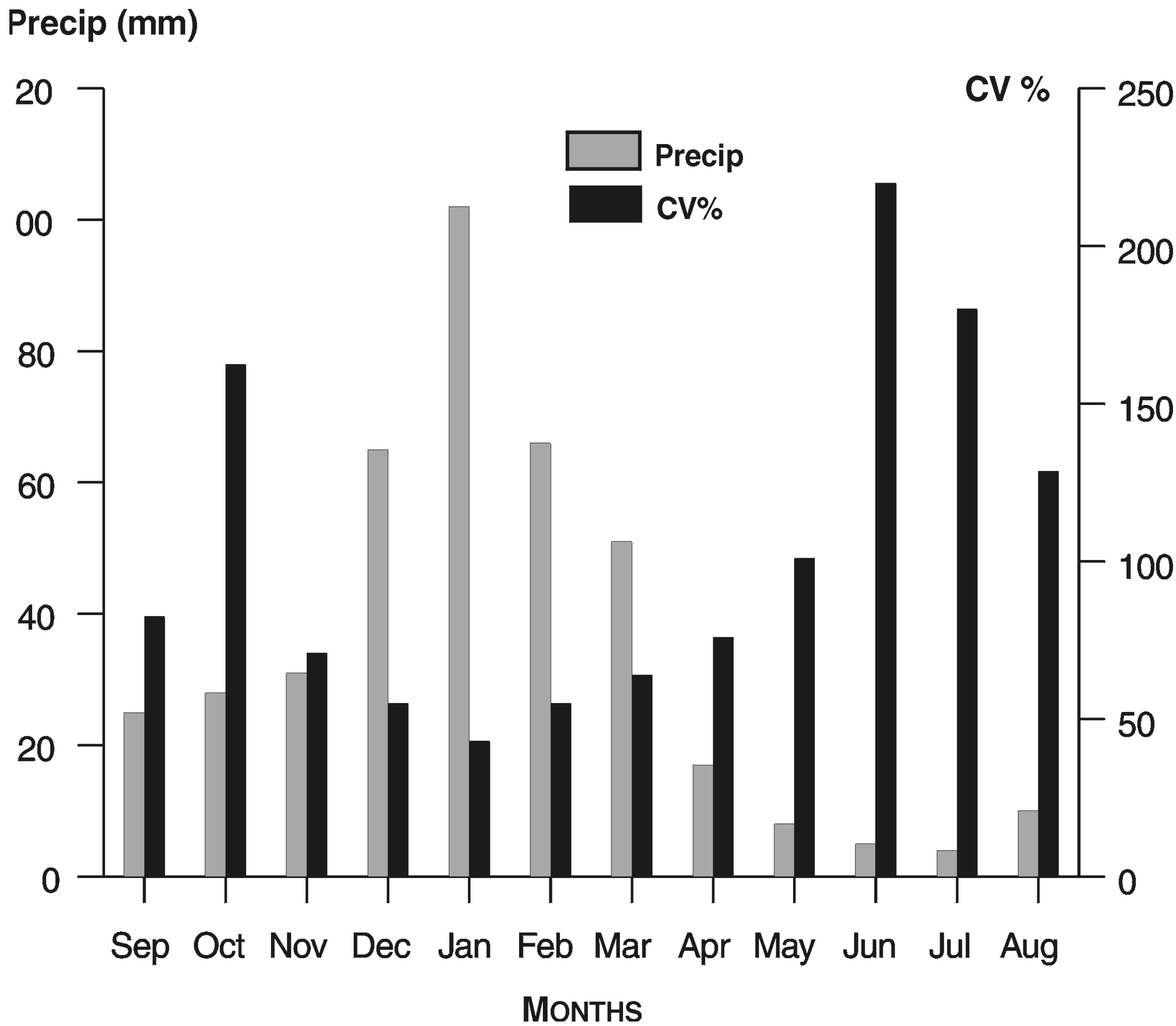


Figure 3.1. *Monthly average precipitation and their coefficients of variation (CV) for the Patacamaya Experiment Station, 1951-94.* Source: Dr. H. Alzérreca (rangeland ecologist, unpublished analysis) based on data collected by INTECSA (1993) and SENAMHI (1994).

Kenya were contrasted to the lower evapotranspiration demands of the cold altiplano, it is likely that the difference in effective moisture between the two types of systems is far greater than that indicated by comparisons based solely on precipitation. Such a crude categorisation of equilibrial versus non-equilibrial dynamics at a systems level, however, is probably too simplistic for several reasons. Evidence is provided later in this chapter to show that different geomorphic units at SJL likely vary in the degree to which precipitation controls the dynamics of plant populations. Geomorphic units, therefore, may be a more appropriate scale of resolution to ascribe equilibrial or non-equilibrial attributes. The units can then be amalgamated into an overall picture of ecosystem structure, dynamics and function.

Our 42 years of climate data are insufficient for making firm conclusions regarding variability and trends. It is interesting to note, however, that a common perception among campesinos at SJL is the the climate is becoming drier (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). Evidence of increasing aridity comes from indications that an old and extensive lake bed at SJL holds ephemeral water much less frequently, or for a shorter period, in recent years compared to the past (see Section 3.3.2.1: *Geomorphic units*). A declining amount of standing water may be related to a medium-term variation in and/or in-

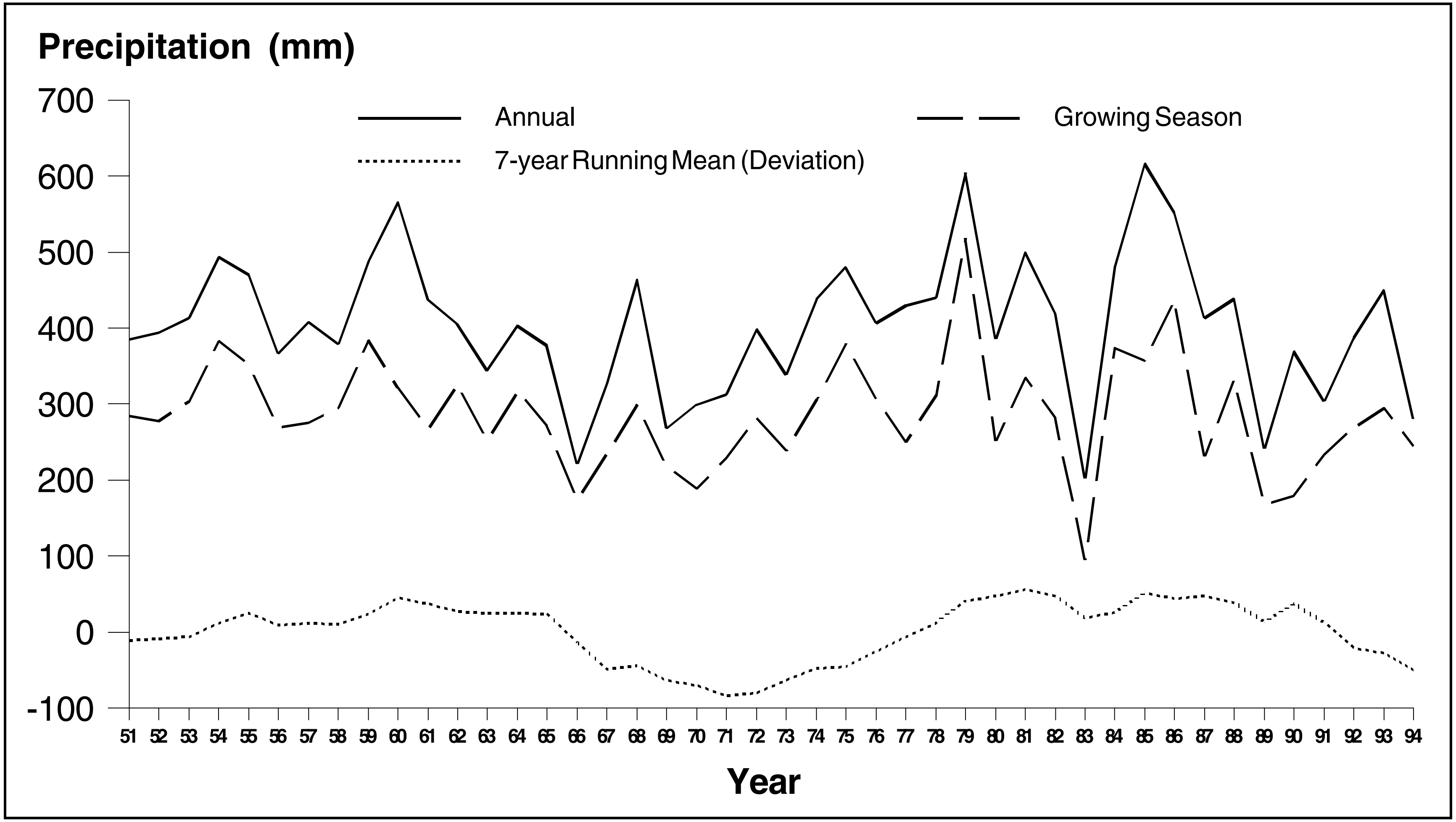


Figure 3.2. *Annual precipitation dynamics at the Patacamaya Experiment Station, 1951-94*. Source: Dr. H. Alzérreca (rangeland ecologist, unpublished analysis) based on data collected by INTECSA (1993) and SENAMHI (1994).

creased demands from upstream users on the flow of rivers that feed into SJL (see below).

If we arbitrarily define a dry year as one in which annual precipitation is <75% of the long-term mean (Cossins and Upton 1988), and a drought as the occurrence of two or more dry years in succession, then some crude probabilities can be calculated based on the 42-year time series if it is assumed that the occurrence of wet and dry years is independent. For example, the chance that a given year will be dry (i.e., with an annual precipitation <300 mm) is thus 7/42 or 0.17. The chance that two consecutive years will be dry (i.e., a two-year drought) is 0.17 x 0.17 = 0.03. Conversely, the chance that two consecutive years will both exceed 75% of the long-term mean is 0.83 x 0.83 = 0.69. The chance that one year will be dry and the other will exceed 75% of the long-term mean is 2 x (0.17 x 0.83) = 0.28. Perturbations to global climate as affected by phenomena such as the El Niño Southern Oscilation (ENSO; Ropelewski 1992) merit consideration as an influence on some patterns of local precipitation. Washington-Allen (1994) cited work interpreted to indicate that the very dry year of 1983-4 at SJL was related to El Niño activity.

If annual precipitation is not independent of that in adjacent years, then use of the probabilities above begins to lose credibility. A possible case-in-point is provided by a graphical presentation of seven-year running means at the bottom of Figure 3.2. The cyclical pattern consisting of alternating blocks of 11 to 13 years in duration can be interpreted to suggest that above-average precipitation tended to occur from 1954-65 and again in 1977-90. One irony, however, is that occurrence of a block having higher or lower rainfall does not preclude the occurrence of unusual years; one example is the very dry year of 1983 happening in the middle of the 1977-90 period of above-average rainfall (Figure 3.2). Factors associated with El Niño have been speculated to play a role in cyclic climate patterns of the Andes. Work by the Cornell University Andes Project (unpublished) has attempted to describe an apparent cycle for levels of Lake Titicaca using a data set going back to 1939. They have found that extended drops in lake levels occur at roughly 10- to 16-year intervals, and that some of these drops coincide with key activity of El Niño. Effects of El Niño have also been implicated in the heavy flooding in the transition zones and lowlands of Bolivia during the early 1980s (INTECSA 1993; see Section 2.2.2.3: *National highlights of social history: 1951 to 1996*).

The high variability of annual precipitation introduces a key element of risk as campesinos plan agricultural activities. Andean campesinos mitigate climatic risk, in part, by diversifying crops and widely distributing cultivated plots across landscapes to take advantage of micro-climatic variability (see below). It is important to note, however, that while researchers have traditionally focused on inter-annual variation in precipitation as an important attribute of agroecosystems, of at least equivalent importance is the monthly or inter-seasonal variability as well as timing of precipitation events. For example, it is well-known that delays in the onset of rains in a growing season can dramatically affect crop production and survival of nursing stock in seasonal environments, even though total precipitation eventually appears “near-normal” on an annual basis (Coppock 1994). The campesinos of SJL cope with a high intra-seasonal variability of precipitation even during peak rainfall months when monthly CVs range from a low of 20% in January (the wettest month of the year at 102 mm) to 110% in June (one of the driest months at 4 mm; Figure 3.1). A comprehensive perspective also needs to include pervasive risk of frost and some losses to diseases and pests such as nematodes (Dollfus 1982; Blanco 1994). Frost risk is discussed below.

3.3.1.2 Air temperature and frost

In seasonal environments at tropical latitudes it is common that seasonality is defined more by temporal variation in precipitation rather than by temporal variation in ambient temperature. This is also the case for SJL. While monthly variation in precipitation is up to 25-fold (i.e., from 4 mm/month to 102 mm/month), monthly variation in mean daily temperature is only 2.4-fold (i.e., from 5 to 12°C). In terms of average daily temperature, May through September tend to be colder (with daily minima below freezing) while October through April tend to be warmer (Table 3.1). The variation between daily maxumum and minimum temperatures exceeds variation among monthly averages. The difference between daily maximum and minimum temperatures varies from nearly 22°C in July to 14°C in February.

In contrast to low-elevation systems in the tropics where environmental perturbations are largely defined by deficits in rainfall (Ellis 1992), frost adds another dimension of abiotic perturbation at SJL, especially when crop cultivation is considered. Frost occurs when both humidity and air temperature decline. When nights are clear and humidity is low, temperatures drop abruptly when the sun sets and this causes frost to form. Frost can severely damage crops (IBTA 1992). Frosts damage plants when ice crystals form in tissues and puncture cell membranes and organelles. Frost-resistant plants utilise several strategies. Going dormant during seasons of high risk of frost is common for perennial native forages on the Altiplano; this takes advantage of the fact that the period of highest frost risk is commonly the time of greatest moisture stress (Dr. H. Alzérreca, rangeland ecologist, personal communication). Other plants like the Andean tubers (i.e., *Solanum tuberosum*, *Ullucus tuberosum*) have their most sensitive, water-holding tissues belowground. Some perennials that have secondary compounds in cellular fluids postulated to serve as a form of "anti-freeze" (shrubs such as *P. lepidophylla*; Dr. H. Alzérreca, rangeland ecologist, personal observation). Frost has also been implicated as having direct and indirect negative effects on the nutritive value of forages, including reductions in crude protein content. Indirect effects on nutritive value occur because photosynthetic activity declines, which lowers production of enzymes and simple sugars.

Monthly incidence of frost at SJL primarily increases as a function of decreasing minimum air temperature. As mentioned above, colder months also tend to be drier. The probability of a frost occurring during a given month is highest during the coldest months when temperatures are most likely to go below freezing. As an illustration, virtually every day in a given June and July can have a frost, while December through March are almost frost-free, on average. Over a longer time frame in a probability framework, there will always be frosts each year from May through August, but nearly four out of five consecutive Januarys will not have one frost (Table 3.1). When frost conditions prevail, the extensiveness of frost on a landscape is affected by topographic location. Frosts will tend to occur more in those depressions and landscape facets where heavier (colder) air collects before sunrise. The warmer the ambient temperature, the more likely frost will be fragmented and localised. The colder the ambient temperature, the more likely that frost will be ubiquitous. Campesinos mitigate frost risk in several ways including use of frost-resistant crop varieties, widespread spatial and temporal distribution of household plots across landscapes, creating new landscapes through large-scale engineering activities, and traditional use of irrigation canals to alter micro-climates in cropping areas.

Precipitation, temperature and risk of frost are inter-related (Le Tacon et al 1992). Cloud cover associated with the rainy season also serves to increase ambient mean temperatures by trapping radiant heat that would otherwise be lost to the atmosphere. Higher ambient temperatures equate to lower risk of frost. Extending this logic further, it would be expected that drier years would have higher risk of frosts. These inter-related factors of precipitation, temperature and frost risk are important for defining the cropping season at SJL. Climate diagrams integrating monthly temperature and precipitation dynamics are presented as Figure 4.4(a-d) in Chapter 4: *Household economy and community dynamics at San José Llanga.*

It is important to note that risks for crop failure can be fairly high even during the primary rainfall months when crop establishment and early growth occurs. For example, despite that January is the wettest and second warmest month at SJL, the cumulative risks of frost or serious moisture deficits adds to a combined probability of 0.60, meaning that in six out of 10 consecutive years, January will experience one form of stress or the other.

3.3.2 Description of natural resources

3.3.2.1 Geomorphic units

Before we delve into the details of geomorphic units, it is important to note a few basic features of SJL with regards to topography. Of particular relevance is the very modest relief throughout the 7200 hectares of SJL; elevation only varies by 61 m overall (i.e., from 3725 to 3786 m). It is also notable that this is a marked contrast to some other agropastoral production systems in the semi-arid puna which incorporate access to valley bottoms for grazing and high mountainsides for cultivation across a wide range of elevation (see Section 2.3.1.2: *Regional environment*). The significance of the 61 m of relief for diversification of agropastoral production at SJL is reviewed later in this chapter.

Simply defined, landscapes are comprised of geomorphic units. Each geomorphic unit can be created differently due to varied effects of wind, water, geology, and in some cases, human activities. Geomorphic units thus have distinct physical and ecological features.

The landscape of the Cantón of SJL may be sub-divided into six basic geomorphic units, mapped in Figure 3.3. Without rigid adherence to geomorphological terminology, and for the sake of brevity, these are referred to as the: (1) Alluvial terrace; (2) alluvial fan; (3) fluvio-lacustrine plain; (4) deltaic deposits; (5) alluvial plain; and (6) eolian deposits. In general, the alluvial terrace and alluvial fan are vital for rain-fed and flood-irrigated cultivation, respectively, of food and forage crops. The fluvio-lacustrine plain is vital as a native range for grazing. The deltaic deposits have recently become important for irrigated cultivation of forage and food crops. The alluvial plain and eolian deposits are small in size and of little or no importance to the agropastoral system overall. These are all defined and described below.

Alluvial terrace. The alluvial terrace is what is left of a former flood plain. It is essentially a core standing remnant (or relict) feature that remains after erosion leveled other portions of the flood plain. The alluvial terrace consists of Luvisols and Lixisols and is situated in the western 25% (or 1800 ha) of the Cantón of SJL (Plate 3.1). The alluvial terrace is where most of the rain-fed cultivation occurs. It lies at the highest average elevation (3786 m) in the cantón, which is about 20 m above the adjacent fluvio-lacustrine plain. This positioning is fortuitous because the slightly higher elevation lowers the likelihood of hard frosts. This attribute has been reported by the campesinos, however, and has not been empirically quantified by research. The alluvial terrace has a gently undulating topography with slopes ranging from 2 to 7%. This unevenness of topography is associated with pronounced micro-climatic variation. Low-lying, concave locales are more prone to frosts than are those which are convex or at mid-slope. Households vary with respect to the distribution of cultivated plots on the alluvial terrace. Households typically have some plots in concave positions and others in convex positions or at mid-slope (C. Jetté, IBTA/SR-CRSP, personal communication).

Alluvial fan. The alluvial fan was formed by sediments deposited by flows of the intermittent, rain-fed (non-saline) *Khora Jahuíra* River as it spills over the banks. The river typically flows from November to May and probably makes “significant” deposits of sediment in most years (Dr J. de Queiroz, IBTA/SR-CRSP, personal observation). Peña (1994) found sediment levels in the river varied from 14.5 to 21.2 g/l during January and March, respectively. The *Khora Jahuíra* River originates in the northwest portion of SJL. The residents of the Cantón of SJL therefore do not have to compete with residents of other cantóns for use of this water. Given the *Khora Jahuíra* River was diverted by SJL residents during the mid-1980s, this is another example of a critical anthropogenic modification of the environment (Figure 3.3; Plate 3.2). The alluvial fan consists of medium-textured Fluvisols and occupies about 15% of the surface area (or 1080 ha) of the cantón. The alluvial fan is mostly used by the campesinos for production of flood-irrigated and sub-irrigated alfalfa (cut-and-carry as well as grazed). There are also flood-irrigated fields of barley (used for animal feed) and native forages for grazing (Chapter 5: *The grazing livestock of San José Llanga*). The overall shape of the top surface of the alluvial fan is slightly convex due to depositional processes. The slope ranges from 1 to 2%. It is important to note that the genesis of this unit is not typical for “natural” alluvial fans as defined in geology texts; purists may thus disagree with this terminological transgression. The alluvial fan at SJL is an artificial, fan-shaped land-unit formed by a man-made river channel. We could find no established geologic term to describe it any better.

Fluvio-lacustrine plain. The fluvio-lacustrine plain is the most extensive geomorphic unit in SJL, covering about 38% (or 2736 ha) of the landscape (Figure 3.3; Plate 3.3). This unit is virtually flat and occupies the lowest landscape position in the Cantón of SJL. It is essentially an old lake bed. The soils consist of Solonchaks having moderate to high levels of salinity. This unit is mostly used by the campesinos for grazing sheep, cattle and

Plate 3.1. *Vista of the alluvial terrace showing early growth on adjacent fields of* quinoa*, barley and potato. The alluvial terrace is the centre for rain-fed cultivation of food crops by virtue of the fresh water supply, good drainage and other favourable soil features.*
Photograph: João S. de Queiroz

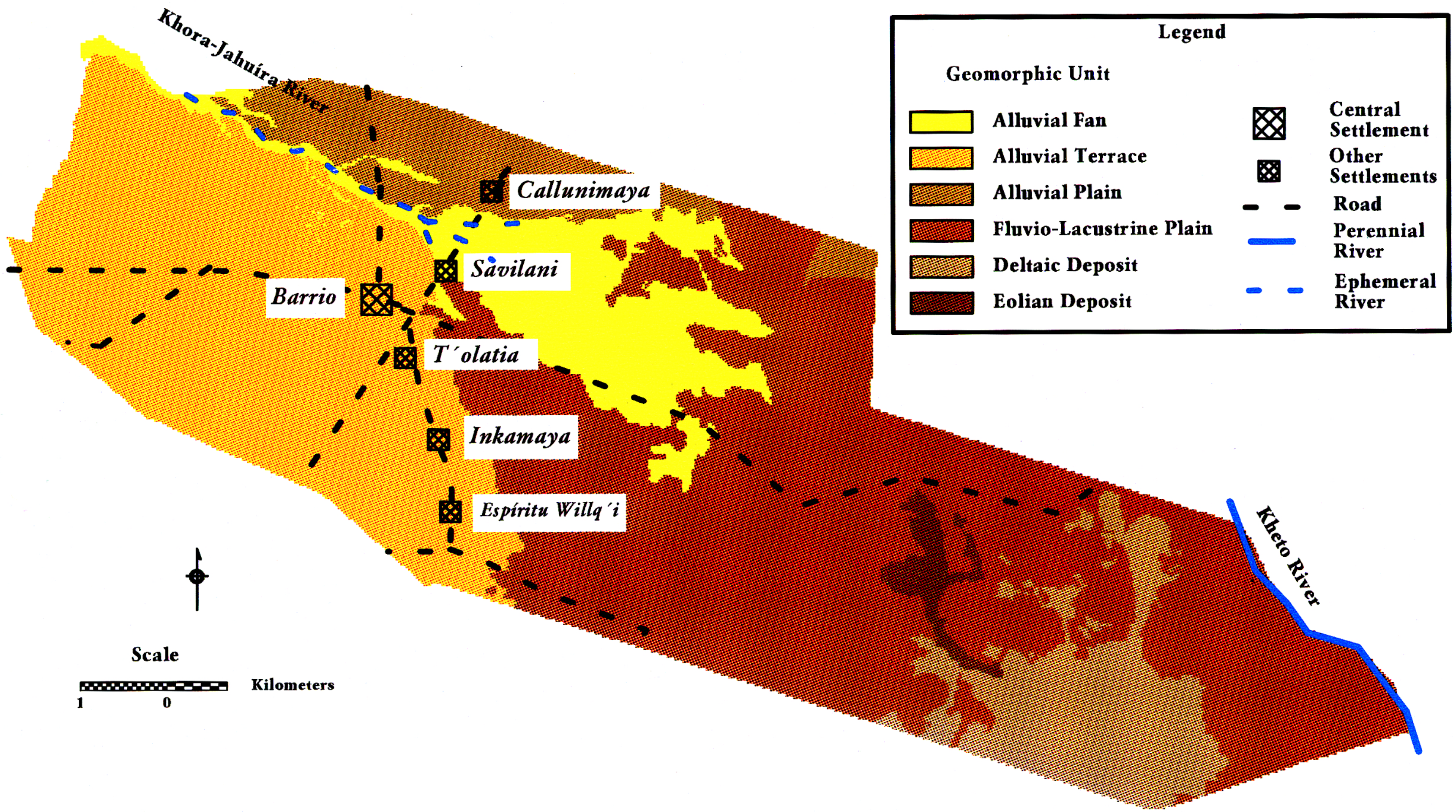


Figure 3.3. Location of six settlements in the agropastoral community of San José Llanga in relation to geomorphic units.
Source: GIS adaptation by R.A. Washington-Allen.

donkeys. Fluvio-lacustrine plains are common on the central Altiplano. They are relicts of numerous, endoreic lakes originally created in the Quaternary Period that expanded or shrank depending on climate (Servant and Fontes 1978; see Section 2.3.1: *Regional highlights of physical geography and environment*). According to campesinos of SJL, prior to the 1970s significant portions of the fluvio-lacustrine plain were commonly underwater throughout the year. This claim was corroborated by examination of aerial photographs from the dry season of 1955 (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). Since the 1970s, however, the fluvio-lacustrine plain has not had standing water during dry seasons, according to local informants. Standing water and a high level of soil saturation are fairly common during the height of the rainy season (Chapter 5: *The grazing livestock of San José Llanga*).

Deltaic deposits. The deltaic deposits are located in the eastern quarter of the cantón and occupy about 10% (or 720 ha) of the landscape (Figure 3.3). The soils are comprised of slightly saline Solonchaks. Although the genesis of this unit is unclear, the relatively coarse soil texture, nearly flat topography, shape and stratigraphic position are congruent with those of sediments deposited by flowing water as it enters a still body of water. The deltaic deposits are used by the campesinos for flood-irrigated alfalfa using saline water from the Desaguadero River (Barrera 1994; reviewed later in this chapter). Barley, *quinoa* and potatoes are also grown on the deltaic deposits under a variety of rain-fed and irrigated conditions.

Alluvial plain and eolian deposits. The alluvial plain occupies a small portion (<9%) of the study area and is sandwiched between the alluvial fan and boundary of SJL with the Cantón Llanga Belén to the northwest (Figure 3.3). The alluvial plain was formed as a result of past flooding. The soils were not surveyed. This unit plays a very limited role in SJL production systems and was thus neglected in our investigations.

Finally, the eolian deposits occur as a small area of small, dune-like formations. They consist of fine, wind-blown sand appended to the deltaic deposits (Figure 3.3). This unit occupies <3% (or 216 ha) of the SJL landscape, and only plays a very limited role in production strategies.

3.3.2.2 Water resources

The water resources of SJL are diverse. Understanding the distribution and other attributes of water is vital to appreciating structure and function of this agroecosystem. Water resources vary in terms of location (i.e., surface versus sub-surface) and chemical quality (i.e., degree of salinity). Location and chemical quality influence the suitability of water for crop irrigation and consumption by people and livestock.

Surface water. As previously reviewed, two rivers have marked influences on the Cantón of SJL. These are the perennial and saline Desaguadero River and the ephemeral, rain-fed

Plate 3.2. *Vista of the alluvial fan showing cattle grazing and cut-and-carry alfalfa harvest. Forage and food crops are nourished by periodic over-flow of the Khora Jahuíra River and roots of alfalfa can access the high water table. The alluvial terrace is a fertile, non-saline site created by the campesinos. It expands due to depositional processes.* Photograph: João S. de Queiroz

Plate 3.3. *Vista of the fluvio-lacustrine plain. This site is a former lake bottom which today is largely comprised of a matrix of various types of native range. These are often defined by variation in salinity and inundation history.* Photograph: Jim Yazman

Khora Jahuíra River. A third, the perennial Kheto River, occurs locally but only affects SJL through rare flooding on the northeastern periphery of the fluvio-lacustrine plain.

The Desaguadero River supplies irrigation to the alfalfa fields on the deltaic deposits. The 23-km, unlined canal used for irrigation was hand-dug by inhabitants of SJL and three neighbouring communities as a response to the 1983-4 drought (Peña 1994; Section 2.4: *Overview of the study area at San José Llanga*). The canal extracts 274 liters per second at its intake point on the Desaguadero River, and 35% of this volume is lost by the time it reaches SJL (Peña 1994). The high salt content of this river water, however, leaves little doubt that irrigation will salinise the deltaic deposits (Peña 1994; see Section 3.3.4.3: *Sustainability of the deltaic deposits*). The river water has a high content of sodium (457 mg/l) and chloride (924 mg/l) according to Peña (1994). Historically, flood waters from the Desaguadero River regularly contributed to the inundation of low-lying areas of SJL, such as the fluvio-lacustrine plain (Mr. Victor Marca, agropastoralist and resident of SJL, personal communication). The frequency of inundations appears to have decreased over the past few decades. The causes for this postulated change have not been established by research.

The *Khora Jahuíra* River flows in an easterly direction and follows an artificial channel that markedly deviates from its original northerly course (Mr. Don Pascual, agropastoralist and resident of SJL, personal communication). This intermittent river enters the Cantón of SJL at the northwest corner and commonly overflows its banks 4 km to the southeast. As previously noted in this chapter, the overflow deposits silt and fine sand to create a well-drained, artificial alluvial fan. Despite that this fan represents only 15% of the landscape, it is perhaps the most important parcel of land for the agropastoral economy at SJL (Section 4.3.3: *Household production system*). The regime of the *Khora Jahuíra* River consists of typically short-lived (<24 hr) periods of turbulent flow, tightly linked with rainfall, that may exceed 4800 liters per second (Peña 1994). While laden with silt and fine sand, water brought to SJL by the *Khora Jahuíra* River poses no chemical problems for plant growth because it is rain-fed (non-saline). On the other hand, there is a significant risk of flooding that can cause physical damage to crops (i.e., alfalfa, barley) on the alluvial fan. The alluvial fan is continually expanding as a result of depositional processes. This can create more acreage for critical agricultural activities such as the cultivation of alfalfa (Dr. H. Alzérreca, rangeland ecologist, personal observation).

The Kheto River forms a portion of the community's eastern boundary and contributes to flooding in the lowest portions of the fluvio-lacustrine plain (Figure 3.3). Due to its location far from the main barrio of SJL, and thus limited relevance to day-to-day activities of the campesinos, this water body was not included in our studies.

Sub-surface water. The entire Cantón of SJL is underlain by groundwater. Under the alluvial terrace where most of the rain-fed cultivation occurs, high-quality ground water of low salinity occurs at between 3 and 10 m depth, depending on topographical location and season. Most dwellings in the communities tap this resource through hand-dug wells. In late 1994 the communities installed a gravity-fed system which directly supplies water to most dwellings.

Under the alluvial fan adjacent to the *Khora Jahuíra* River, the water table is between 2 and 3 m beneath the soil surface, well within reach of alfalfa roots. The electrical conductivity of ground water (ECw) for the alluvial fan is low [i.e., <0.08 Siemens/meter (or S/m) from Peña (1994)], indicating a low degree of salinity and suitability for irrigation. Non-saline flood waters from the *Khora Jahuíra* River replenish the water table in most years. Access of roots to ground water allows perennial alfalfa to green-up in October, which is in the critical transition period between the end of the dry season and beginning of the wet season. Green-up of alfalfa is facilitated by a gradual increase in temperature, which also diminishes the likelihood of hard frosts. The nutritional status of livestock is commonly poorest at this time, and access to green alfalfa provides a critical boost (Chapter 5: *The grazing livestock of San José Llanga*). It is important to note as an aside that alfalfa, a crucial production intervention for the SJL system, has been grown at SJL for many years. Significant increases in the establishment of small-scale alfalfa fields were first noted at SJL in the 1960s when there was a push to expand production of improved sheep breeds among the campesinos. This initiative was spearheaded by staff of the Patacamaya Experiment Station in concert with consultants from Utah State University, who in turn worked under the auspices of USAID (Dr. H. Alzérreca, rangeland ecologist, personal communication). Alfalfa cultivation subsequently further expanded in the 1980s and early 1990s at SJL when smallholder dairying took hold

(Chapter 4: *Household economy and community dynamics at San José Llanga*).

The entire fluvio-lacustrine plain is underlain by perched water tables sandwiched between impervious layers of clay or silt. They are not aquifers in a technical sense and are quite small in size. The depth of the water table under the fluvio-lacustrine plain ranges from 0.6 to 1.5 m (Peña 1994) with ECw values ranging from 6.0 to 0.04 S/m (Peña 1994; Garabito 1995). The lowest ECw values occur in a small area adjacent to the alluvial fan and alluvial terrace where the bulk of the human population resides (Figure 3.3). This can be interpreted to suggest that the location of the main barrio and satellite communities has been influenced by access to potable water and proximity to the rain-fed cropping fields of the alluvial terrace. Towards the center of the fluvio-lacustrine plain the ECw values exceed 2.4 S/m, which is unsuitable for use by most plants. Out of 14 wells sampled by Peña (1994) on the fluvio-lacustrine plain in November (prior to the onset of the rainy season), 10 were either unsuitable or only marginally suitable for irrigation due to high salinity. The proportion of highly saline water samples would have probably been higher if the sample points had been selected randomly, rather than extracting samples from hand-dug wells (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). The quality of ground water under the fluvio-lacustrine plain may also markedly change over short distances. For example, Garabito (1995) measured differences in ECw in excess of 5.5 S/m between sample points that were only 9 m apart. This phenomena occurs because pockets of sub-surface water are segregated by a honeycomb of impervious layers of silt and clay. Accordingly, quality of water from the 54 hand-dug wells across the fluvio-lacustrine plain varies tremendously (Peña 1994; Plate 3.4). Perforation of sub-surface clay and silt lenses by more hand-dug wells will result in more mixing of ground water and homogenisation of water quality over time (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation).

The depth to the water table under the deltaic deposits ranges from 1.6 to 2.4 m in depth (Peña 1994). Values for ECw range from 0.8 to 1.3 S/m, making this ground water only marginally suitable for irrigation.

3.3.2.3 Soils

About 81% of the soil resources of the Cantón of SJL were surveyed (Table 3.2). The sites that were not surveyed included those associated with the alluvial plain, a site type of very marginal significance to the production system overall.

The surveyed area was almost evenly divided into those soils which were salt-affected and those which were not. The former tend to occur at lower-elevation sites having higher water tables and periodic flooding; grazing is the most common form of land use for salt-affected soils. Soils not affected by salinity occur at slightly higher elevations, tend to have been modified by human engineering in some cases, and are well-drained; cultivation is the most common form of land use on soils not affected by salinity. This cultivation takes the form of either rain-fed or flood irrigated; the latter relies on fresh water associated with the *Khora Jahuíra* River. Some descriptions and details for constituent soil types follow.

Saline soils. Nearly 45% of the area surveyed for soil features at SJL is covered by salt-affected soils. These are called Solonchaks under the revised legend of the Soil Map of the World (FAO/UNESCO/ISRIC 1988). Guided by Garabito's (1995) study of soil-vegetation relationships, which was conducted at ecotones within salt-affected areas of SJL, we used conductivity of a saturation extract (ECe) from samples at the soil surface to sub-divide Solonchaks into three sub-types. This was required because the legend of the Soil Map of the World was inadequate to accommodate the range of salinity encountered at SJL. Thus, we defined: (1) Hyper-saline Solonchaks as soils with an ECe value for the surface horizon >2.5 S/m; (2) moderately saline Solonchaks as soils with an ECe value for the surface horizon between 0.4 and 2.4 S/m; and (3) slightly saline Solonchaks as

Plate 3.4. *Example of a hand-dug well for livestock use in a hyper-saline portion of the fluvio-lacustrine plain.* Photograph: João S. de Queiroz

Table 3.2. *Selected chemical and physical features of common surface soils at San José Llanga.* Sources: Adapted from Peña (1994) and Miranda (1995).

Soil Type	Feature[1]						
	Surface ECe (S m^{-1})	pH	Depth of Water Table (m)	Surface Texture[2]	OM (%)	Drainage[3]	Percent of Area
Hyper-Saline Solonchaks	2.3-11.2	7.3-8.1	0.8-2.0	c, cl	0.1-0.9	poor	18.2
Moderately Saline Solonchaks	0.4-2.3	7.9-9.7	0.8-1.6	c	3.1-7.5	poor	18.5
Slightly Saline Solonchaks	<0.4	7.5-8.0	>2.0	sl	--	good	7.8
Medium-textured Fluvisols	<0.4	7.5-8.5	>2.0	ls,sl	0.6-1.4	good	11.9
Fine-textured Fluvisols	0.1-1.0	8.3-8.5	0.6-0.8	c,sil	3.2-3.4	poor	3.6
Luvisol/Lixisol association	<0.1	7.3-7.7	>3.0	s,ls	0.2-1.1	good	21.0
Other (not surveyed)	--	--	--	--	--	--	18.7

[1]Where surface ECe is conductivity (indicative of salinity), OM is organic matter, and percent of area is the approximate percentage the soil type comprised of the entire Cantón of San José Llanga.

[2]Where c=clay, cl=clay-loam, ls=loamy sand, sl=sandy loam, sil=silt-loam.

[3]Where "poor" drainage was indicated when water ponded on the soil surface for two days or more after heavy rainfall. "Good" drainage was indicated when there was no ponding of water on the soil surface after heavy rainfall.

soils with an ECe value for the surface horizon <0.4 S/m.

Hyper-saline Solonchaks covered 18% of the surveyed area (Table 3.2), but they are present only within the fluvio-lacustrine plain (Figures 3.3 and 3.4). These are fine-textured, poorly drained soils, usually subtended by a water table within 1.5 m of the soil surface (Peña 1994). Surface horizons tended to have a lower content of organic matter (OM) and a slight to moderate alkalinity (Miranda 1995). The low OM content likely occurs because these soils now support little vegetation and tend to be poorly drained. Because of extreme salinity levels and poor drainage, these soils support a restricted suite of halophytic (i.e., salt-tolerant) species with a prostrate or cushion-shaped morphology; these include *Salicornia pulvinata*, *Anthobrium triandrum* and *Atriplex nitrophylloides*. In the wet season these soils become waterlogged and are an important impediment to the movement of people and livestock in SJL. This is a factor that plays a role in grazing management decisions (see Chapter 5: *The grazing livestock of San José Llanga*).

Moderately saline Solonchaks are also restricted to the fluvio-lacustrine plain (Figures 3.3 and 3.4). These soils occupied about 18.5% of the surveyed area. They are fine-textured, poorly drained and alkaline with surface pH values reaching 9.7 when percent of exchangeable sodium is high (Table 3.2). The water table is often within 1.5 m of the surface. Surface soil horizons may have high levels of OM (Miranda 1995). Often the moderately saline Solonchaks are covered by low-growing rhizomatous and stoloniferous grasses such as *Distichlis humilis* and *Muhlenbergia fastigiata.* Where grazing pressure is relatively low, *Hordeum muticum* becomes an important component of vegetation communities. Other factors may also influence persistence of *H. muticum* in these sites (Dr. H. Alzérreca, rangeland ecologist, personal communication). Management factors aside, *H. muticum* is known as a frost-tolerant species that can grow at low temperatures, hence its highly regarded status as a forage. Considering management, grazing commonly occurs on the fluvio-lacustrine plain during dry seasons, due in part to periodic inundation or at least extreme muddiness of these sites during wet seasons (see Chapter 5: *The grazing livestock of San José Llanga*). Dry season grazing therefore defoliates plants when they are dormant, sparing the more grazing-sensitive species such as *H. muticum*. In addition, traditional practices of water spreading using low, extensive earthen walls on the fluvio-lacustrine plains may have expanded the suitable habitat for *H. muticum*. This has been the case in similar communities of the semi-arid puna (Dr. H. Alzérreca, rangeland ecologist, personal communication).

Slightly saline Solonchaks primarily occur on the deltaic deposits (Figures 3.3 and 3.4) and occupy 7.8% of the surveyed area. They are coarse-textured and well-drained soils with a water table situated >1.5 m from the soil surface (Peña 1994; Miranda 1995). The pH values for surface horizons range from slightly to moderately alkaline (Table 3.2). These soils are being used for irrigated cultivation of cereal crops (i.e., barley, *quinoa*) and alfalfa. A few campesinos have small patches of forage grasses such as *Dactylis glomerata* and *Agropyron* spp. The presence of salt-tolerant *A. triandrum* as a dominant species in fallow fields on the deltaic deposits has been interpreted as an indication of increased soil salinity due to use of irrigation water from the Desaguadero River (Peña 1994).

Non-saline soils. Medium-textured (Calcaric) Fluvisols covered about 12% of the surveyed area. These are young soils restricted to the artificially created alluvial fan (Figures 3.3 and 3.4). They are well-drained, moderately alkaline and subtended by a deep water table (Table 3.2). Surface and sub-surface textures vary from loamy sand to sandy loam. Frequent wet-season flooding by the *Khora Jahuíra* River adds sediments, moisture and nutrients which all contribute to make this patch of soil a key resource. Whereas elevated risk of frosts and floods limit potato cultivation on these soils, the presence of good quality sub-surface water, nutrients and good drainage make this site well-suited for alfalfa cultivation. Frost-tolerant annual forages such as barley also do well on these medium-textured Fluvisols (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation).

Fine-textured (Mollic) Fluvisols occur in the fluvio-lacustrine plain adjacent to the alluvial fan and near the boundary with the alluvial terrace (Figures 3.3 and 3.4). These poorly drained soils occupied 3.6% of the surveyed area. Fine-textured Fluvisols are characterised by alkalinity and a relatively high OM content irregularly distributed with depth (Miranda 1995). While mostly non-saline, some patches do exhibit saline properties as defined by the revised legend of FAO/UNESCO/ISRIC (1988). Fine-textured Fluvisols support highly productive vegetation types typified by *Calamagrostis curvula* and *Festuca dolichophylla*.

Luvisols and Lixisols covered 21% of the surveyed area. Barrera (1994) found these soils to comprise the alluvial terrace where the bulk of community production of food-crops (i.e., potatoes, *quinoa*) takes place (Figures 3.3 and 3.4). These soils have a coarse-textured surface horizon which lies over a medium- to fine-textured horizon of clay. Luvisols and Lixisols are slightly alkaline with low concentrations of OM and soluble salts (Table 3.2). They are well drained and have a low water-holding capacity. The sandy surface is devoid of structure and prone to wind erosion. Small-scale, wind-blown deposits are found throughout the alluvial terrace, especially down-wind from cultivated fields.

3.3.2.4 Land cover

About 90% of the landscape of SJL was surveyed in terms of land cover. The 11 land-cover types are listed in Table 3.3. Only nine land-cover types are mapped in Figure 3.5, however. This is for a couple of reasons. One is that some cover types occurred as patches that were scaled too small to appear in Figure 3.5. The second reason was that sites designated as "early successional herbfield" or *kallpas* were deemed distinct enough to merit their own land-cover designation, but because this was only an ephemeral stage of food-crop production they were all mapped together as "food crops." The major land-cover types are briefly defined and described below.

Cultivated lands. Cultivated lands are those which produce either annual crops for people and livestock or perennial forages for livestock. The lands yielding the annual crops tend to be rain-fed and have substantial acreage in fallow. Lands yielding perennial forages have a combination of sub-irrigation, surface irrigation and rain-fed components and little or no fallow. Cultivated lands are also referred to by the generic term Cades.

Annual food and forage crops and fallow. The first focus for land-cover is on sites used for production of annual crops. Annual food crops like potato and *quinoa* and annual forages like barley and wheat are vital components of the agroecological system at SJL. Potato and *quinoa* are primarily grown under rain-fed conditions on the alluvial terrace, which is comprised of soils in the Luvisol/Lixisol association (Treadwell and Libermann 1992; Barrera 1994). Barley is by far the most popular annual forage crop, with wheat a distant second choice as annual forage (Barrera 1994). Barley and wheat are primarily grown via flood irrigation and rain-fed means on the artificial alluvial fan, which is comprised of coarse-textured Fluvisols.

Cropping cycles and rotations for each food and forage crop are discussed in detail in Ciro and Cáceres (1994) and Barrera (1994). Crop sequences change depending on the subtending geomorphological unit (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). The most common sequence on the alluvial terrace is a year of potatoes followed by a year of *quinoa* and then fallow. The next most-common sequence is potatoes followed by *quinoa*, barley and fallow. On the alluvial fan a common sequence is barley followed by alfalfa; there are several others which also use barley as the first crop. On the deltaic deposits the sequence of barley followed by alfalfa is most common.

For purposes of this chapter, however, general similarities in crop cycles for rain-fed annuals will be emphasised. For example, for potato, *quinoa* and rain-fed barley and wheat it can be broadly asserted that the cycle consists of up to three years of repeated cultivation on a given field, followed by an extended fallow of <15 years. In most cases fallowing appears to result in a re-establishment of native vegetation, which tends to be a mix of short, evergreen shrubs and perennial bunchgrasses on these sites (see below). The cropping cycle is re-initiated when animal draught power or tractor tillage is used to plough up later successional stages of native vegetation and create a barren, sandy substrate. The extended fallow is a traditional practice dictated by constraints of climate, soil infertility and attempts to manage soil-borne pests such as nematodes. Impacts of modernisation are probably altering some aspects of the traditional cropping cycle in both positive and negative ways (see Section 3.3.4: *Integration of ecological findings*).

The rain-fed fallow consists of a couple of distinct stages in land cover, lumped here as an early stage and a later stage. During the first three to four years, fallow fields are dominated by annual herbs or forbs as an early successional stage. This is locally referred to as *kallpas* in *Aymara* vernacular (Cáceres 1994; Ortega et al 1995; Table 3.3; Plate 3.5). *Kallpas* offers important grazing at certain times of the year (Chapter 5: *The grazing livestock of San José Llanga*). *Kallpas* occurs as small patches (i.e., from 0.25 to 1.0 ha in size; Barrera 1994) interspersed within another, more extensive cover type called *tholares*. *Tholares* is the shrub-dominated, cover type indicative of an advanced stage of successional recovery. *Tholares*

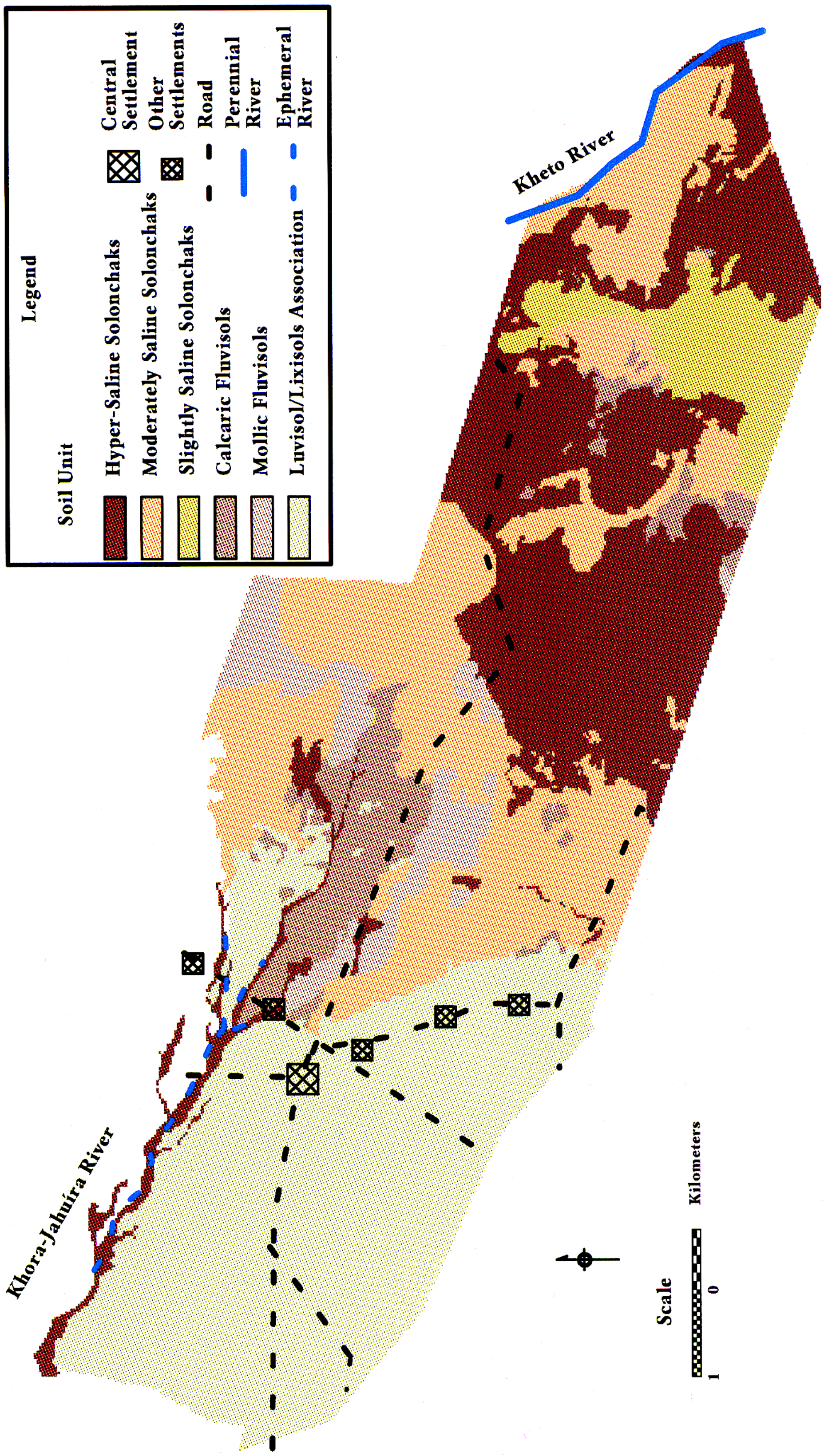


Figure 3.4. Soil units for the agropastoral community of San José Llanga. Settlements and roads are included for orientation. The area covered by this map is 5832 ha (58 km²). The alluvial plain north of the Khora-Jahuíra River was not surveyed. Soil classification follows FAO/UNESCO/ISRIC (1988) classification. Source: GIS adaption by R.A. Washington-Allen from Treadwell and Libermann (1992).

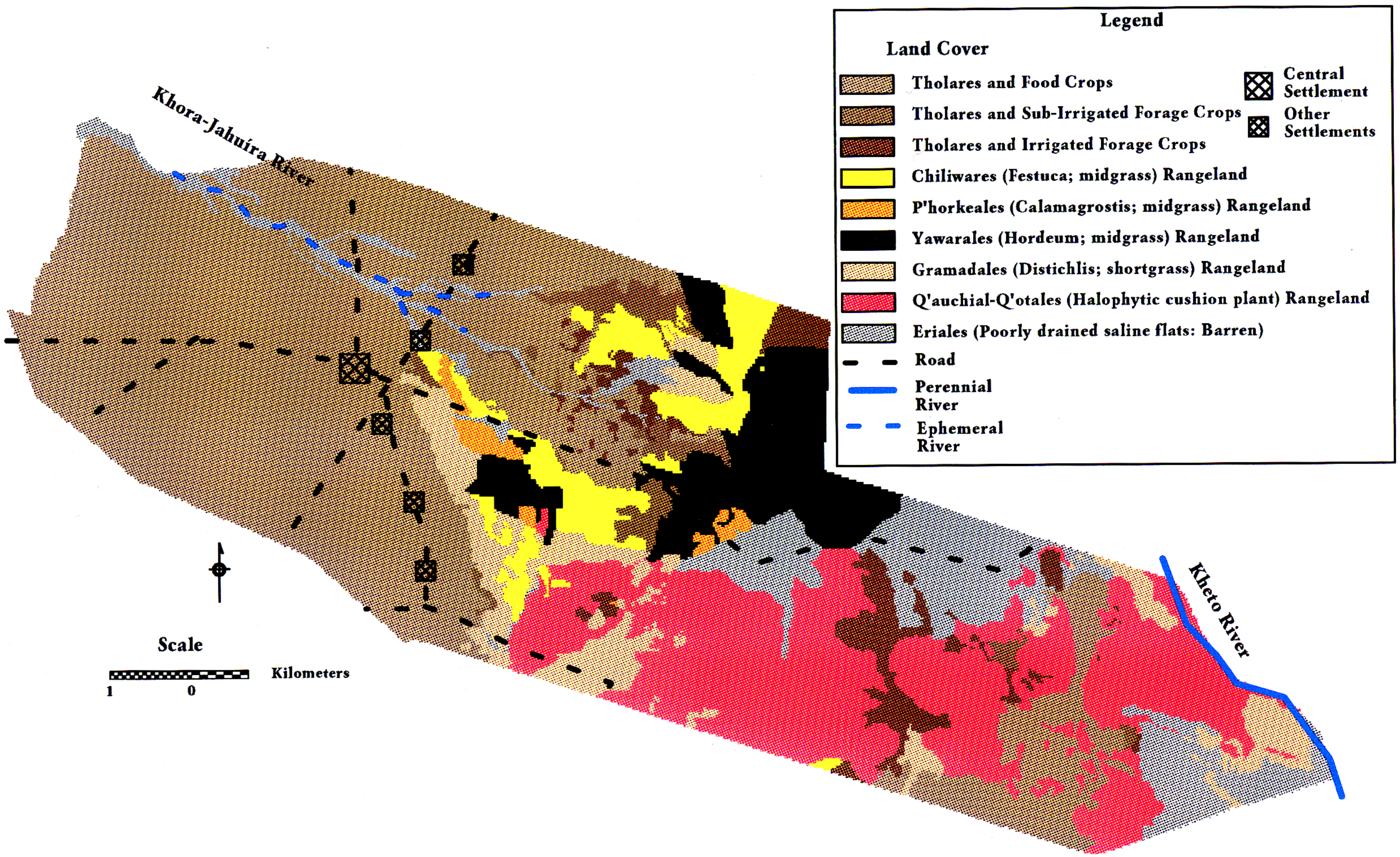


Figure 3.5. Land cover types for the agropastoral community of San José Llanga. Settlements and roads are included for orientation. The area covered by this map is 7200 ha (72 km²). Source: Land cover classification follows Treadwell and Libermann (1992) with GIS adaption by R.A. Washington-Allen.

Table 3.3. *Features of selected land-cover types in San Jose Llanga*. Source: Adapted from Miranda (1995).

Land Cover Type[1]	Characteristic Plant Species	Other Common Plant Species	Soil Unit
Kallpas (early successional herbfields)	*Chenopodium petiolare, Bouteloua simplex,*	*Erodium cicutarium, Tarasa tenella, Heterosperma tenuisecta, Gnaphalium lacteum*	Luvisol/Lixisols, Slightly Saline Solonchaks, Medium-textured Fluvisols
Tholares (late successional shrub-bunchgrass fields)	*Parastrephia lepidophylla, Festuca orthophylla*	*Stipa ichu, Tetraglotchin cristatum, Nasella pubiflora, Astragalus* spp.	Luvisol/Lixisols, Slightly Saline Solonchaks, Medium-textured Fluvisols
Annual forage crops	*Hordeum vulgare, Triticum aestivum*	NA	Luvisol/Lixisols, Slightly Saline Solonchaks, Medium-textured Fluvisols
Food crops	*Chenopodium quinoa Solanum tuberosum*	NA	Luvisols/Lixisols, Slightly Saline Solonchaks
Alfalfares	*Medicago sativa*	NA	Medium-textured Fluvisols, Slightly saline Solonchaks
Q'auchiales-Q'otales	*Salicornia pulvinata, Anthobrium triandrum*	*Atriplex nitrophiloides, D. humilis*	Hyper-saline Solonchaks
Eriales	NA (barren)	NA	Hyper-saline Solonchaks
Yawarales	*Hordeum muticum,*	*Muhlenbergia fastigiata, Eleocharis albibracteata, D. humilis*	Moderately saline Solonchaks
Gramadales	*D. humilis, M. fastigiata*	*E. albibracteata S.pulvinata, A. thriandrum*	Moderately saline Solonchaks
Chilliwares	*Festuca dolichophylla,*	*H. muticum, M. fastigiata, Calamagrostis curvula, D. humilis*	Fine-textured Fluvisols
P'horkeales	*C. curvula*	*H. muticum, F. dolichophylla, D. humilis, M. fastigiata*	Fine-textured Fluvisols

[1]Where *Kallpas* and *tholares* were two stages of crop fallow, while annual forage crops and food crops were currently planted fields. *Alfalfares* were surface and sub-irrigated alfalfa plots. The other six land cover types were on native rangelands.

is characterized by the low-growing shrub *Parastrephia lepidophylla* (or *thola* in *Aymara* vernacular; Plate 3.5). *Tholares* in itself provides important resources for grazing (bunchgrasses) and fuel wood (shrubs). In the SJL region *tholares* succeeds *kallpas* after four to five years of fallow. *Kallpas* and *tholares* are lumped as one mapping unit called "*Tholares* and food crops" in Figure 3.5.

Assuming a cropping sequence of three years on a given field (Barrera 1994), an average field size of 1.0 ha (Barrera 1994), a total of about 2500 fields (C. Jetté, IBTA/SR-CRSP, personal observation) and a cropped:fallow ratio of 1:5 (Norton 1992), we estimated that *kallpas* occupies about 500 ha of the SJL landscape and *tholares* occupies another 1500 ha. It must be noted, however, that these are only rough estimates. A lower estimate would result if figures of Ortega et al (1995) had been used. They estimated SJL had 3000 crop fields averaging 0.36 ha in size, which results in a total coverage of 180 ha for *kallpas*. Barrera's (1994) estimates were used here because he measured about 53 fields selected on a stratified-random basis across three geomorphic units. Using information from Barrera (1994) as well as data from Norton (1992) that 43, 36 and 21% of the cropped fields supported potato, *quinoa* and barley or wheat, respectively, the area planted to various crops can be estimated. From this we surmise that about 395 ha was dedicated to food crops, with 105 ha dedicated to cultivated annual forages, during our study period. More information on cropping and crop yields is reviewed in Chapter 4: *Household economy and community dynamics at San José Llanga*.

Perennial cultivated forage. *Alfalfares* is the vernacular term for irrigated alfalfa fields (Table 3.3; Plate 2.8c). These occur only on the alluvial fan and deltaic deposits. As previously noted, on the alluvial fan alfalfa roots tap slightly saline groundwater (Peña 1994). In the second case alfalfa is flood irrigated with saline water from the Desaguadero River. Based on visual estimates from the map of Treadwell and Liebermann (1992), it appears that the *alfalfares* occupies between 70 to 100 ha of the SJL landscape. As previously mentioned, the *alfalfares* is a vital component of animal production strategies for sheep and dairy cattle. Under local management the alfalfa is treated as a long-lived (20+ years) perennial crop. The preferred alfalfa variety is "Ranger". Other varieties are used depending on seed availability (Dr. H. Alzérreca, rangeland ecologist, personal observation).

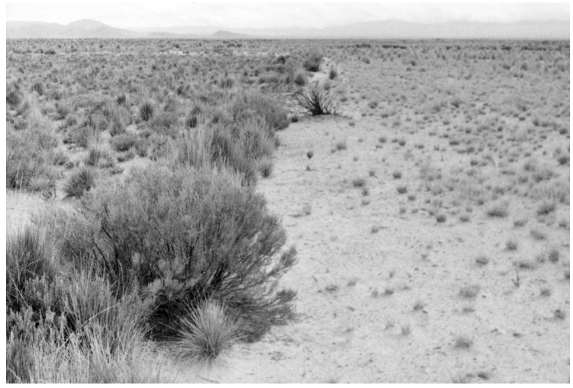


Plate 3.5. *Extremes of the ecological succession on cultivated fields of the alluvial terrace are shown with adjacent fields of climax* tholares *dominated by shrubs and bunch grasses (to the left) and annual herb fields called* kallpas *(to the right). This scene also illustrates the high structural diversity of adjacent sites in the crop plot matrix. Mature* thola *shrubs* (Parastrephia lepidophylla) *are important sources of fuelwood while* kallpas *is important for sheep grazing.* Photograph: Christian Jetté

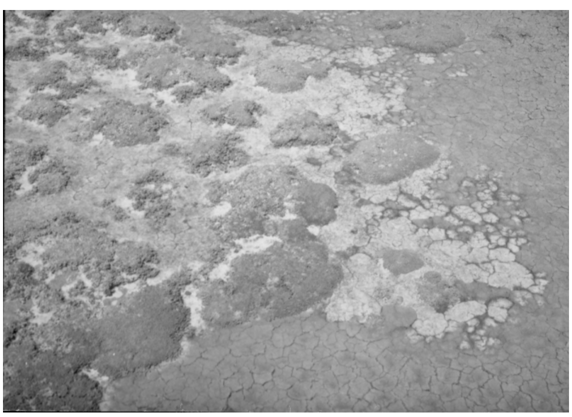
Rangelands. Overall, rangelands add to almost half of the landscape area of SJL. The rangelands consist of native plant communities and supplied grazing for roughly 5000 sheep, 500 cattle and 125 donkeys during the course of our research (Chapter 5: *The grazing livestock of San José Llanga*). The poorer quality rangelands are communally used and managed, while some of the higher quality rangelands may be privately annexed by households if precipitation has been high and grazing resources are abundant. Conversely, all grazing areas become communal during dry years and droughts (see Chapter 5: *The grazing livestock of San José Llanga*). The major land-cover types of rangeland at SJL are briefly defined and described below.

Rangeland having high soil salinity. The association dominated by salt-tolerant cushion plants (*Salicornia pulvinata* and *Anthobrium triandrum*) dispersed on otherwise nearly denuded ground covers about 1700 ha (or 62 % of the grazing lands) at SJL and primarily occurs on hyper-saline Solonchaks at lower points in the fluvio-lacustrine plain (Figures 3.4 and 3.5 and Plate 3.6a,b). In *Aymara* vernacular these associations are referred to as *q'auchiales-q'otales*. Both species of cushion plants are capable of withstanding soils with an ECe >12 S/m. There are a few associated woody and herbaceous species (Table 3.3). Whereas *S. pulvinata* appears to be an obligatory halophyte, *A. triandrum* is not because it also occurs on non-saline soils. For example, Garabito (1995) found that *S. pulvinata* cover tends to peak when ECe varies from 6.0 to 8.0 S/m, while that for *A. triandrum* peaks when ECe <2.5 S/m. Although these vegetation types only provide very limited forage for grazing sheep (<200 Kg DM/ha; Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation), they are valued more for their contributions to supplement the mineral content of livestock diets, with a particular benefit in terms of the flavor imparted to meat. For example, local informants claimed that meat from sheep reared in areas with *q'auchiales* and *q'otales* have superior taste compared to those reared in non-saline environments (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). Such sheep meat may have a premium price in local markets (Dr. H. Alzérreca, rangeland ecologist, personal observation).

Rangeland having moderate to low soil salinity. *Eriales* is the name ascribed to barren patches of saline rangelands that occur across 280 ha in the central portion of the fluvio-lacustrine plain (Table 3.3; Figures 3.4 and 3.5). Contrary to our expectations, *eriales* were not necessarily more saline than *q'auchiales, q'otales* or even some areas of well-vegetated *gramadales* (Garabito 1995; Miranda 1995; *gramadales* are described below). This is interpreted to indicate that soil salinity is not the only reason for the occurrence of *eriales*. Garabito (1995) presents evidence to support the hypothesis that populations of *S. pulvinata* are invading the *eriales*. In other cases we observed where stands of the perennial grass *H. muticum* (a species associated with non-saline soils; see below) had colonised patches of previously barren *eriales*. We suspect that *eriales* reflect a past hydrologic regime when the central portion of the fluvio-lacustrine plains was submerged for long periods of time. We believe that the frequency and duration of floods at SJL have diminished over the past decade, and this has allowed a variety of salt-tolerant and other plants to recently invade and grow on what once were totally barren patches.

Yawarales are vegetation stands characterized by *H. muticum*, a perennial, erect grass with a wispy panicle locally known as *yawara* in SJL (Plate 3.7). Associated species were described by Massy (1994) and are listed in Table 3.3. Stands of *H. muticum* are regarded as very valuable for grazing by sheep and cattle (Ramos 1995). *Hordeum muticum* communities also occur on moderately saline Solonchak soils within the fluvio-lacustrine plain, with the largest patch located about six kilometers east of the main barrio of SJL (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). Access to distant patches of yawarales is made difficult during periods of heavy rainfall due to poor drainage characteristic of the soils of the fluvio-lacustrine plains. The *yawarales* occupy about 450 ha of SJL overall.

The *gramadales* consist of heavily grazed patches of vegetation dominated by perennial, low-growing (or prostrate) and stoloniferous grasses such as *D. humilis* (or *chiji blanco*) and *M. fastigiata* (or *chiji negro*). This community is depicted in Plate 3.8. The balance between these two species shifts with changes in soil salinity; *D. humilis* becomes



a

b

Plate 3.6 (a,b). *Land cover (*q'auchiales *and* q'otales*) associated with the hyper-saline Solonchaks of the fluvio-lacustrine plain: (a) Close-up of key species such as* Salicornia pulvinata *on a* q'auchiales *site and (b) a wide-angle view of a* q'otales *site with* Anthobrium triandrum. Photographs: (a) Brien E. Norton and (b) João S. de Queiroz more dominant as salinity increases (Garabito 1995). Associated species were initially described by Massy (1994) and are listed in Table 3.3. This vegetation type is restricted to about 520 ha of poorly drained, mostly salt-affected soils within the fluvio-lacustrine plain (Dr. J. de Queiroz, IBTA/ SR-CRSP, personal observation). It tends to skirt the boundary between the fluvio-lacustrine plain and the alluvial terrace (Figures 3.4 and 3.5). By virtue of its position on the landscape the *gramadale*s is heavily used for grazing throughout the year (Victoria 1994; Ramos 1995), but is not among the highest quality site-types (below). Where soil salinity has an ECe <1.0 S/m, we believe that *gramadale*s result from heavy grazing which has eliminated highly palatable species such as *H. muticum* (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). The carpet-like canopy created by *D. humilis* and *M. fastigiata* appears to be extremely stable and resistant to incursions by other, possibly less-tenacious species. This interpretation is supported by the fact that *H. muticum* grows well along vehicle tracks where the dense canopy typical of gramadales has been opened. Another factor may be that *H. muticum* benefits from water accumulation in vehicle tracks (Dr. H. Alzérreca, rangeland ecologist, personal communication). Thus, we have speculated that patches of *gramadales* in heavily grazed areas represent a degraded, but stable, vegetation state. These may be especially prevalent in “sacrifice zones” nearer to homesteads and corrals which are subject to continuous grazing. It is important to note, however, that this label of “degradation” is from the standpoint of livestock production. Due to its low-growing habit and relatively low productivity [i.e., 3.87 t DM/ha reported by Prieto and Yazman (1995)], the *gramadales* are regarded as most suitable for grazing by Criollo sheep. Improved sheep may also graze *gramadales* for short periods of time. Cattle are commonly precluded from grazing *gramadales* due to the low-growing habit of the dominant forages (Dr. H. Alzérreca, rangeland ecologist, personal observation).

Chilliwares derive its name from *chilliwa*, the *Aymara* name given to *Festuca dolichophyll*a, the characteristic species of this vegetation type (Plate 3.9). This highly productive (7.6 t DM/ha; Prieto and Yazman 1995) vegetation type occupies about 300 ha (or 11%) of the fluvio-lacustrine plain on fine-textured Fluvisols to the west. Soils are high in OM and relatively low in soluble salts (Miranda 1995). Common species within the *chilliwares* are listed in Table 3.3. The *chilliwares* are considered an important grazing resource by the campesinos of SJL.

P'horkeales are vegetation stands characterized by *Calamagrostis curvula* (or *p'horke* in *Aymara* vernacular), a coarse, rhizomatous grass of moderate palatability (Ramos 1995). These sites occur on <5% of the fluvio-lacustrine plain. Associated species are listed in Table 3.3. According to the campesinos, *C. curvula* tends to increase with heavy grazing at the expense of more palatable grasses such as *H. muticum* and *F. dolichophylla*.

Plate 3.7. *Land cover associated with mixed-grass communities called* yawarales *on the fluvio-lacustrine plain (peak growth following the rainy season). Species such as tall* Hordeum muticum *are regarded as valuable forages.* Yawarales *occur on moderately saline soils.* Photograph: João S. de Queiroz

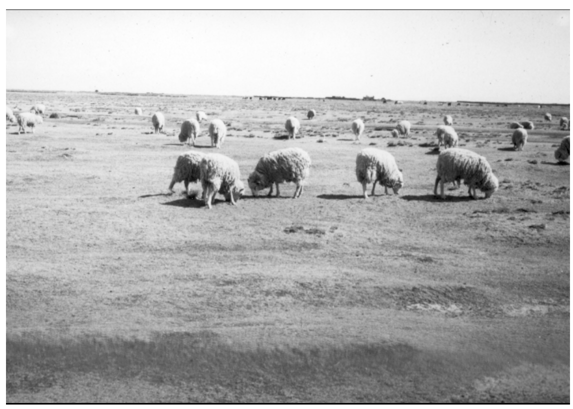


Plate 3.8. *Land cover associated with the short-grass communities called* gramadales *which occurs between the fluvio-lacustrine plain and alluvial terrace. Species such as* Distichlis humilis *are low-growing and tolerant of moderate salinity. The* gramadales *is one of the few range types where plant species composition has likely been degraded by heavy grazing, especially near settlements where livestock activity increases.* Photograph: João S. de Queiroz

Plate 3.9. *Land cover associated with the mixed-grass communities called* chilliwares *which occur on moderate to lightly saline soils on the fluvio-lacustrine plain. Species such as* Festuca dolichophylla *are regarded as valuable forages.* Photograph: Christian Jetté

When *p'horkeales* are heavily grazed *H. muticum* is found primarily within tufts of *C. curvula* where it can escape repeated defoliation (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). *P'horkeales* are highly productive [7.9 t DM/ha; Prieto and Yazman (1995)] and tend to be heavily grazed due to their proximity to the main barrio of SJL where livestock are corralled at night.

3.3.3 Natural resource dynamics

3.3.3.1 Photosynthetic activity of herbaceous vegetation

In rangeland environments worldwide it is typical that growth of vegetation is related to periods when temperatures are favourable and there is a positive balance for soil moisture. These conditions most often occur during and shortly after the main wet season(s). In very hot climates where evapotranspiration rates are high and the water holding capacity of soils is low, growing periods can thus be very short. Woody plants often have longer growth periods than herbaceous plants in such settings because the deeper root systems of woody plants provide access to soil moisture unavailable to herbaceous plants which can only exploit upper soil horizons (Coppock 1985). Conversely, length of growing period increases when climates are more moderate and water holding capacity of soils is higher. This picture is made more complicated, however, when herbaceous plants gain access to reliable ground water, and the linkage between plant growth and precipitation events is weakened. The rangelands of SJL exhibit complexity in patterns of photosynthetic activity. This can be traced to variation in geomorphology, associated quality and accessibility of ground water, and other features of climate (e.g., moisture, temperature) and forage interactions.

Considering first the alluvial terrace, photosynthetic activity by herbaceous cultivated and native species is closely coupled with rainfall. The elevated nature of the alluvial terrace means that herbaceous plants do not have access to ground water. Thus, herbaceous plant growth on the alluvial terrace is largely initiated with the onset of the rainy season in November or December and may continue to June. Harvest time for potatoes is typically in April, while harvest time for barley occurs in May or June (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). Native plants such as thola shrubs or herbaceous species may grow well into the cold, dry season if soil moisture is available (Peréz 1994).

In contrast to the alluvial terrace, situations in the low-lying alluvial fan and fluvio-lacustrine plain are different. Washington-Allen's (1994) analysis of six satellite images obtained for 1972-87 revealed limited photosynthetic activity (as indicated by TNDVI) during the late dry-season months of August (1986-7) and September (1987) in rangeland areas covered by *gramadales* (or *Distichlis/ Muhlenbergia*), *p'horkeales* (or *Calamagrostis*), *yawarales* (or *Hordeum*) and *chilliwares* (or *Festuca*). Vigorous photosynthetic activity, however, was evident in the same vegetation types at the very end of the dry season (October) in 1986, through the end of the following wet season in May, 1987. The most persistent green patches were in the vicinity of the boundary between the alluvial terrace and fluvio-lacustrine plain, an area dominated by *gramadales*, *p'horkeales* and *chilliwares*. These are locations where water salinity is low and the water table is relatively closer to the soil surface (Peña 1994). A similar pattern was observed for alfalfa on the alluvial fan in 1994, which was also an "average" rainfall year (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). These alfalfa fields were dormant in the cold, dry season but resumed growth by early October, 1994, when green forage was badly needed for livestock. This surge of alfalfa production, however, was probably mitigated by the frequent hard frosts which occurred until mid-November when air temperature began to increase.

We interpret the results of Washington-Allen (1994) and other field observations to suggest the following: for low-lying rangeland plant communities of SJL where ground water is accessible to herbaceous plants but happens to be less saline, length of growing season is determined, to some extent, by temperature (i.e., restricted by hard frosts) rather than rainfall. Furthermore, because availability of ground water is only loosely coupled to local rainfall (Peña 1994), the patches of sub-irrigated, higher quality range and the cultivated alluvial fan serve as important buffers which help the system mitigate against climatic variability. These resources resemble one facet of "key resources" for rangeland systems proposed by Scoones (1991).

3.3.3.2 Biomass dynamics for selected rangeland vegetation types

Prieto and Yazman (1995) estimated monthly standing crops for three vegetation types in the low-lying rangelands (Figure 3.6). For *Calamagrostis* (*p'horkeales*) the peak biomass (1.8 t DM/ha) occurred in March; rates of ANPP varied from 3 to 6 kg DM/ha/day in January and February, respectively. For *Festuca* (*chilliwares*) the peak biomass (2.0 t DM/ha) also occurred in March; rates of ANPP were around 21.6 kg DM/ha/day over the preceding two months. In contrast, for *Distichlis/ Muhlenbergia* (*gramadales*) the peak biomass was much lower (0.9 t DM/ha) and occurred in April; rates of ANPP averaged about 7 kg DM/ha/day. Standing crops precipitously declined from May to August as the cold, dry season progressed. Losses of biomass were largely due to weathering in these protected sites.

It is difficult to elaborate on results of Prieto and Yazman (1995) because they did not provide climate data for their period of study. It is surmised, however, that rates of production would shift at least slightly from year to year depending on the timing of rainfall and hard frosts. Because each of the three vegetation types is situated over readily accessible ground water, the apparent abrupt decline in ANPP beginning in April is interpreted to suggest that the growing period was curtailed by cold temperatures (frosts) rather than lack of moisture. According to data presented in Table 3.1, the incidence of frosts increases 10-fold in April compared to that for December through March.

3.3.3.3 Seasonal changes in CP content for selected native forages

Concentration of crude protein (CP) for three important forage species studied by Prieto and Yazman (1995) peaked either in January or February (Figure 3.7). Peak values coincide with the period of early growth having higher soil moisture and warmer temperatures. Table 3.4 shows seasonal quality of forages selected by livestock. This illustrates the high nutritive value of forbs in the growing period. It also illustrates that CP content declined for grasses and forbs in the dry season relative to the growing season. Results overall were thus consistent with young plants having higher relative concentrations of cell solubles relative to cell wall and higher proportions of leaf versus stem (Van Soest 1994).

The overall pattern that forage quality declines with time (i.e., with increasing plant maturity) is in agreement with the literature (Van Soest 1994). The small number of samples analysed each month, however, makes it impossible to assess meaningful variation among species across months. The data are interpreted to suggest some interesting trends, and some speculation is provided. The pattern can be interpreted to indicate that some species may decline more rapidly in forage value than others. For example, CP content for *C. curvula* and *M. fastigiata* appeared to linearly decline to values between 5.0 and 6.1% by the second half of the cold, dry season. Considering conventional guidelines that dietary CP content should not decline <7.0% for proper maintenance of ruminal fermentation (Van Soest 1994), one can infer that tissues of *C. curvula* and *M. fastigiata* were below minimum requirements as early as May and July of this year, respectively. In contrast, CP content for *H. muticum* may have remained above 8.0% through August. These results agree with ranking of forage species by campesinos at SJL reported by Ramos (1995) in which *H. muticum* was rated as the highest quality native species for grazing, while *M. fastigiata* and *C. curvula* were ranked as "average" forages. How *H. muticum* could maintain a higher CP value for a greater length of time is unclear. The simplest explanation is related to species and site factors: *H. muticum* may exist in sites where it can better access the ground water, and therefore remain greener longer. No root excavations were performed on this species to confirm this idea, however. In addition, *H. muticum* could have a higher degree of frost tolerance (previously discussed). It is common to observe green *H. muticum* near permanent sources of fresh water at the height of the cold, dry season. This can be interpreted to suggest that *H. muticum* is more sensitive to moisture

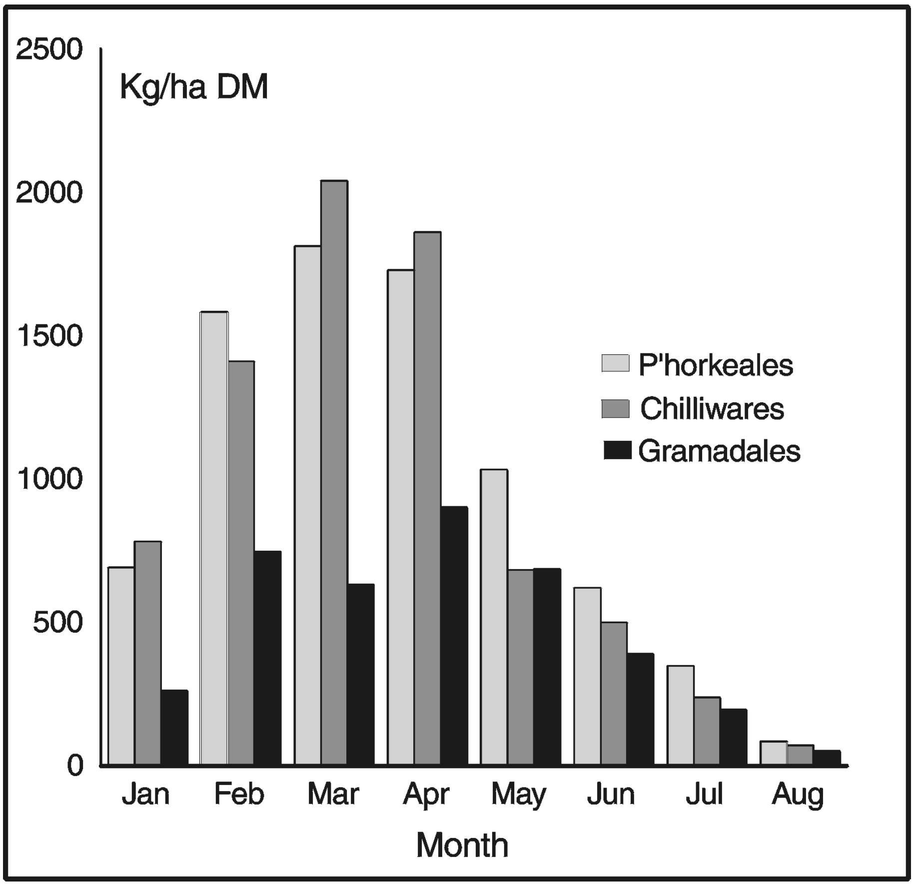


Figure 3.6. *Monthly dynamics of standing biomass (dry matter in kg/ha) for three range community types protected by exclosures at San José Llanga from January through August, 1995. Each bar value represents the mean of three observations.* Source: Prieto and Yazman (1995)

availability than cold (Dr. H. Alzérreca, rangeland ecologist, personal observation).

3.3.3.4 Vegetation change on fallow fields

The character of vegetation in fallow fields changes with length of fallow. As vegetation composition and structure shifts so does its value for grazing (Ramos 1995) and fuel wood (Barrera 1994). Communal rules govern use of fallow land, and the rules change with length of fallow (Chapter 5: *The grazing livestock of San José Llanga*). The sheer size (up to 500 ha) and productive potential of fallow on the alluvial terrace makes fallow a vital resource to the community of SJL. An understanding of vegetation dynamics in fallow fields is crucial, therefore, to understanding agropastoral production strategies.

Analysis of space-for-time relations has been interpreted to suggest that total plant cover on fallow fields remains relatively constant during the first five years (Cáceres 1994). A focus on total cover, however, masks large, gradual changes in cover composition that occur according to plant species. For example, Ramos (1995) found that across six or more years of fallow the relative abundance of coarse perennial grasses (i.e., *F. orthophylla*) and shrubs (i.e., *P. lepidophylla*) increased by nearly 10- and 20-fold, respectively, while cover of palatable annual forbs and grasses declined (Figure 3.8a,b). The decrease in cover of annual *Chenopodium petiolare* [the most desirable forage within fallow fields, according to Ramos (1995)] after the fourth year of fallowing is of particular importance, along with declines in cover of other palatable annuals such as *Boutelona simplex* and *Tarasa tenella*. This temporal change in plant species composition and grazing value justifies differing controls exerted by the community

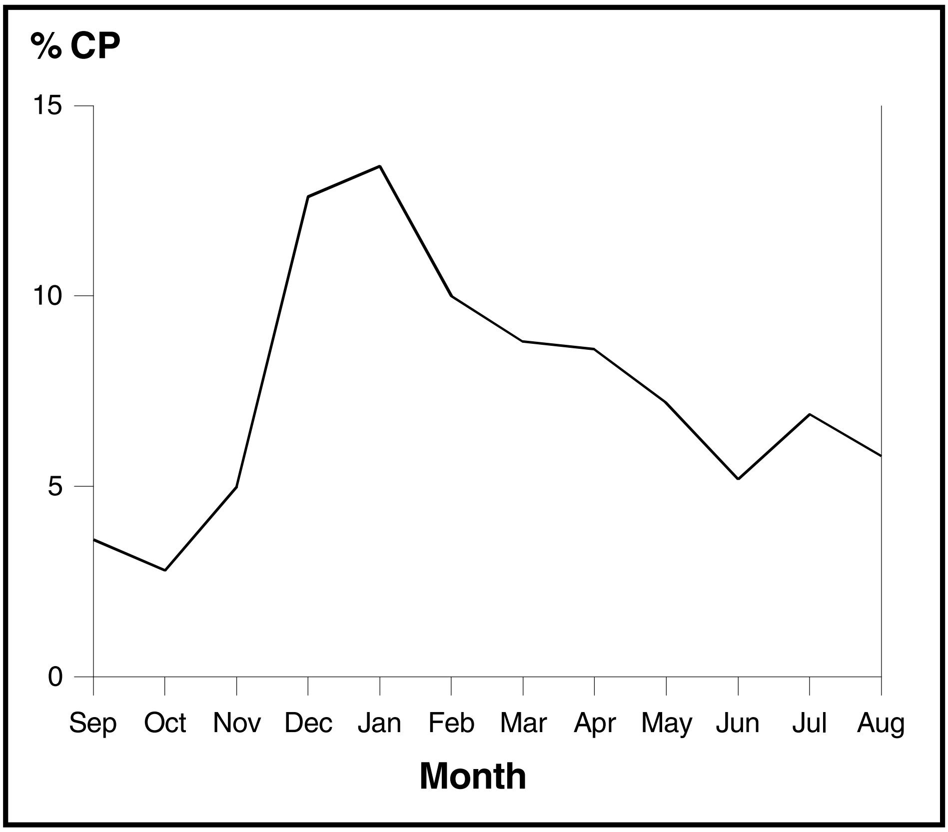


Figure 3.7. *Crude protein content (CP%) on a dry-matter basis of important grass, forb and shrub forages selected by three livestock species (i.e., sheep, cattle and donkeys) by month throughout the year at San José Llanga during 1992-3. The period November through March approximates the main growing season for rain-fed plants while April through October constitutes the dry season. Each data point represents the mean for 14-15 observations. Forages were selected on a mix of sites including crop fallow (mostly forbs) and rangeland.* Source: Lopéz (1994, 125)

over fallow fields. Those in fallow <4 years are treated as a privately owned and managed resource, whereas those in fallow for longer periods are treated as common property (Ramos 1995). The exact mechanisms of successional changes on fallow fields remain unclear (see below).

In another study that focused exclusively on perennial plant species on fallow fields, Queiroz et al (1994) found that the suite of perennial species in fallow fields tended to stabilise after the fifth year of fallowing. On the other hand, density and cover of the shrub *P. lepidophylla* (or *thola*) continued to increase, reaching peak values between eight to 10 years on the Luvisol/Lixisol soil association and 11 to 12 years on the medium-textured Fluvisols of the alluvial fan (Figure 3.9a,b). A decrease in cover and density of shrubs in fields under fallow for longer periods may be due to losses from fuel wood harvesting (Barrera 1994) or age-related shrub mortality. Shrub density and cover on medium-textured Fluvisols was over twice that on Luvisols/Lixisols (Figure 3.9a,b). This difference could be related to the more accessible water table for the Fluvisols associated with the alluvial fan.

As reviewed elsewhere (Chapter 4: *Household economy and community dynamics at San José Llanga*) biomass of mature *thola* is extensively collected by the campesinos. It is used either in the home as fuel for cooking (especially bread) or to generate income. *Thola* is sold to traders who fill large trucks with the material and transport it to urban centres for fuel (Plate 3.10a,b). Given this importance of *thola* as fuel, a study was conducted by Barrera (1994) to determine biomass yields associated with mature plants (>40 cm in height) which are the ones typically harvested for fuel. Plants are harvested with a pick and collected

Table 3.4. *Crude protein content (CP%) on a dry-matter basis of 180 samples of important grass, forb and shrub forages*[1] *selected by three livestock species (i.e., sheep, cattle, and donkeys) during the wet and dry season, and pooled over both seasons, at San José Llanga during 1992-3. Forages were selected from a mix of sites including crop fallow (mostly forbs) and rangeland.* Source: Lopéz (1994).

	Time Period							
	Growing Season[2]			Dry Season[2]			Overall[3]	
Forage Class	n	$\bar{x}$	SE	n	$\bar{x}$	SE	n	$\bar{x}$
Grasses	32	8.6	0.79	48	6.2	0.40	80	7.1a
Forbs	27	12.9	1.00	29	7.3	0.58	56	10.0b
Shrubs	7	8.2	1.46	7	8.4	1.89	14	8.3ab

[1]Hand-plucked samples simulated materials selected by livestock (Lopéz 1994).

[2]Where the growing season for plants dependent on rainfall was November through March and the dry season was April through October.

[3]Means in this column accompanied by the same letter (a,b) were not significantly different (P>0.05) according to Fisher's LSD test (Lopéz 1994). Means were based on 14-15 samples each.

material includes aboveground and belowground wood. Barrera (1994) estimated that up to 40% of the harvested biomass per plant may be comprised of the crown and upper root mass. Harvestable, standing-crop biomass (air-dried basis) for *thola* peaked between 8 and 10 years of fallowing on Luvisols/Lixisols and 11 to 15 years of fallowing on Fluvisols (Table 3.5). The peak biomass accumulation on fluvisols was 4-fold that on Luvisols/ Lixisols. The proportion of biomass suitable as fuelwood increased as plants aged, ranging from 6% for plants in fields fallowed <3 years to over 50% for plants in fields fallowed for >11 years.

The description of vegetation changes on fallow fields presented above is interpreted to suggest that: (1) the value of forage decreases with duration of fallow; (2) there is little further change in the suite of species present within a given field after the fourth or fifth year of fallow; (3) the production of fallow field vegetation varies tremendously with soil type at SJL; (4) there is a pronounced change over time in vegetation structure and woody biomass accumulation up to around 11 years of fallowing; and (5) secondary succession on fallow fields is somewhat predictable.

Studies on the agroecology of fallowing have been conducted by other investigators at the campesino community of Pumani, located 50 km to the northeast of the Cantón of SJL. While some of the work at Pumani has revealed that fallowing for up to five years increased soil fertility, there were no clear effects of fallowing for more than five years on soil nutrient content (Hervé 1994). Also in Pumani, Cary and Hervé (1994) were able to show only a weak correlation between length of fallow and soil microbial populations. Instead, they found that during the first five years of fallow microbial activity was more strongly influenced by the preceding cropping regime. At a similar altitude to SJL, in the Department of Cusco, Peru, Blanco (1994) found that the number of potato nematodes decreased with length of fallow for a period of up to five years, beyond which no nematodes were found.

Taken together with our studies in SJL, the results of Blanco (1994), Hervé (1994) and Cary and Hervé (1994) may be interpreted to indicate that from the standpoint of grazing value, pest control and soil fertility there is little justification for extending fallow periods on the semi-arid puna be-

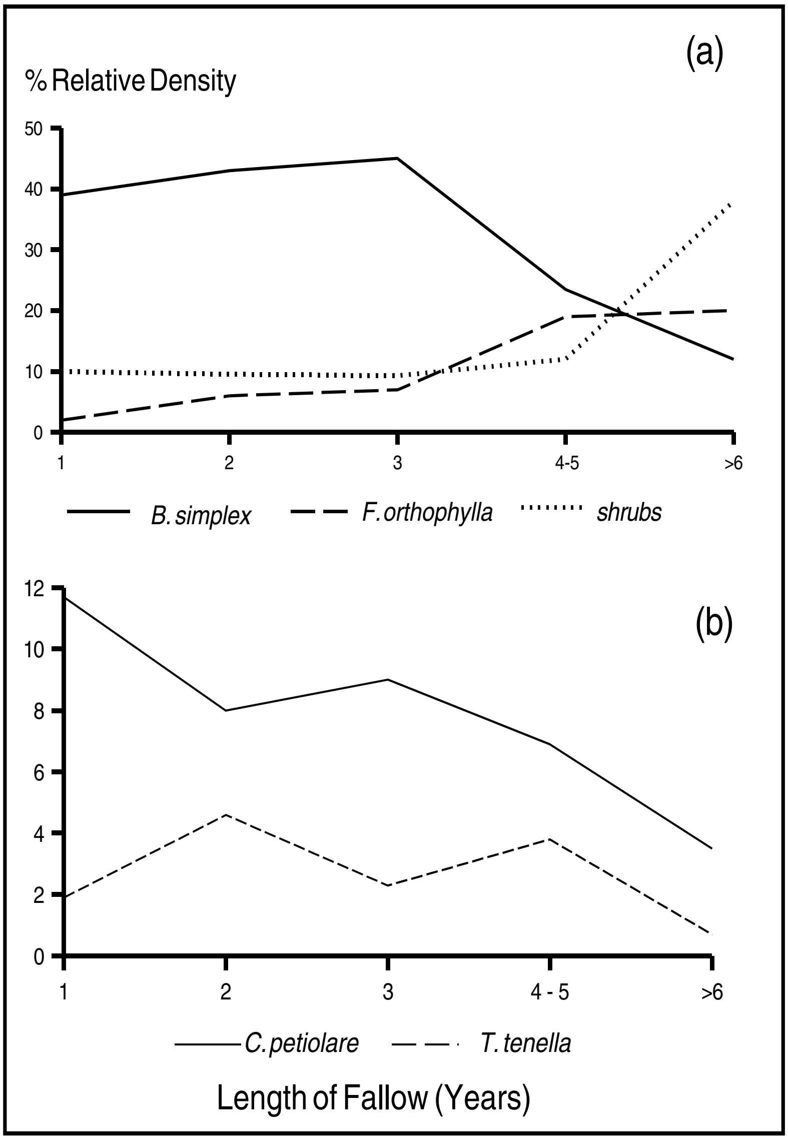


Figure 3.8 (a,b). *Changes in relative crown cover (%) for selected plant species over time on fallow fields on the alluvial terrace at San José Llanga: (a) is where species cover was calculated on the basis of total vegetation cover while (b) is where species cover was calculated on the basis of total cover that includes bareground, plant litter, etc. In both cases cover response over time was regarded as a continuous response variable.* Source: Adapted from data in Ramos (1995)

yond five years. If this is true, the paradox is that shortening the fallow period at SJL by an average of six (or more) years could have a large effect on boosting food production if the area devoted to cropland is limiting. On the other hand, however, continued increases in woody biomass (and thus fuelwood) with increased length of fallow up to about 11 years, and the possibility to sustainably harvest and market fuel wood, could suggest that fallow periods longer than five years are justified from a multiple-use perspective that includes fuel wood production (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). Alternatively, results from Pumani may not be transferable to SJL, and the long fallow at SJL may be symptomatic of a gradual deterioration in soil quality and variable suitability of plots for sustained cultivation (C. Jetté and Dr. L. Markowitz, IBTA/SR-CRSP, personal communications). In addition, fewer households may be regularly engaged in cultivation due to the increasing prevalence of economic activity off-farm. Thus a lengthening fallow may be related

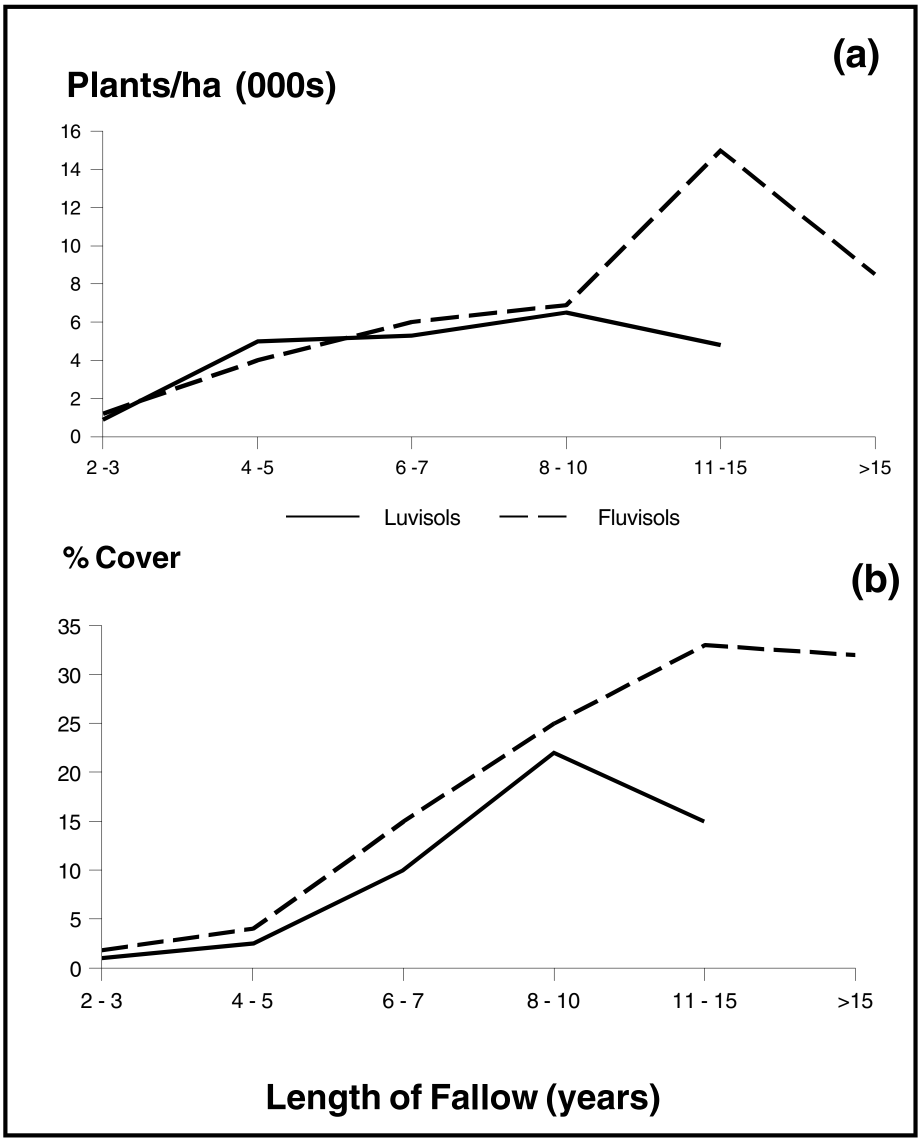
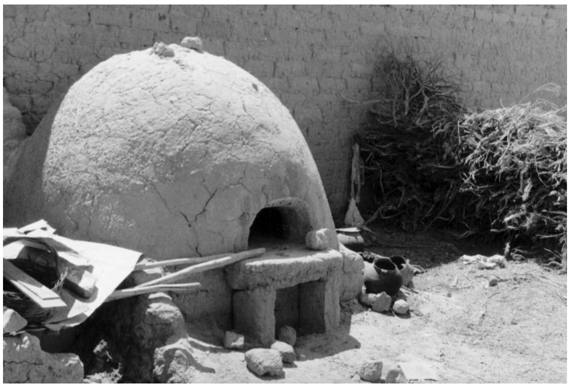


Figure 3.9 (a,b) *Changes in relative crown cover (%) and density (no./ha) for the shrub* Parastrephia lepidophylla (thola) *over time on fallow fields occuring on: (a) Luvisol/Lixisols associations and (b) medium-textured Fluvisols. Cover and density responses over time were regarded as continuous response variables. Source: Adapted from Queiroz et al (1994)*

simply to more absentee farmers and variability in access to labour (Dr. L. Markowitz, IBTA/SR-CRSP, personal communication). In sum, many social and biological factors are likely responsible for determining duration of fallow periods.

3.3.3.5 Soil movement among fallow fields

Although Barrera's (1994) rudimentary study of soil movement in fallow fields of SJL was statistically deficient, the results provide some practical insights into effects of wind erosion on the alluvial terrace. Barrera (1994) concluded that during the cold, dry season there was considerable redistribution of soil among fallow fields, but not necessarily a net loss overall. Between two consecutive monthly readings the level of the soil surface either rose or dropped around each of five, randomly located rods in each of the five fallow fields. The variation in soil-surface level was more pronounced in fields under fallow for <4 years; these differences ranged up to 9 mm per rod. These younger fields were characterised by having lower total plant



a

b

Plate 3.10 (a,b). *Uses of local shrubs* (P. lepidophylla *or* thola) *including: (a) Fuel for baking bread in a traditional kiln at San José Llanga and (b) export of shrubs via truck to generate cash income for local campesinos. Truck drivers then sell the shrubs in urban areas.* Photographs: Christian Jetté

cover than older fields, and thus wind movement of surface soil on younger fields could be more pervasive.

By assuming a soil bulk density of 1.5 g/cm^3 and averaging changes in soil surface level across the five rods in each field the three months of observation, Barrera (1994) estimated the weight of soil material deposited or removed within the five fields. Every field had zones of deflation and deposition; however, those under fallow for <4 years experienced a net soil loss, whereas fields under fallow from five to six years experienced a net soil gain. More specifically, fields under fallow from two to three years lost 69 and 33 metric tons of soil per hectare, respectively. Fields under fallow from five to six years gained 30 and 42 metric tons of soil per hectare.

In spite of its limitations, Barrera's (1994) study can be interpreted to indicate that a large proportion of wind-blown soil remains within the alluvial terrace. This localised redistribution occurs because current agricultural practices produce a checkerboard of small fallow fields supporting physiognomically distinct vegetation types. Thus, soil materials blown from cropped and recently fallowed fields are trapped by adjacent areas supporting a significant cover of shrubs and perennial grasses. Were larger contiguous areas to be subjected to cultivation in a given year, the magnitude of soil erosion in terms of spatial displacement and amount of material lost to the system is bound to dramatically increase (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). On the other hand, even under the current pattern of land-use, as the soil material is transported between fields fine-sized clay and silt particles are removed in suspension, which reduces the nutrient- and water-holding capacity of the surface horizon. In some cases, surface soil removal has exposed the hard argic “B” horizon typical of Lixisols and Luvisols. Thus, the adoption of practices to control soil erosion could enhance the performance of the agronomic component of the SJL agropastoral system. A return to using regular application of sheep manure to cultivated fields could do much to increase OM content of soils; this would enhance the structure of soil surfaces, increase fertility, better distribute seeds of annuals and reduce erosion (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). In recent times chemical fertilisers have been purchased by the campesinos at SJL to replace animal manures. Manures, in turn, have increasingly become a cash crop sold out of the system. These and related issues are reviewed at length in Chapter 4: *Household economy and community dynamics at San José Llanga*.

3.3.3.6 Ecotone migration in the saline rangelands

Garabito (1995) studied ecotones in the saline areas of the fluvio-lacustrine plains. Ecotones are boundaries between ecological site types. Ecotones may exhibit sudden or gradual changes in ecological features, and this gives clues as to what

Table 3.5. *Accumulation of total above-ground biomass and biomass as fuel wood for specimens of* Parastrephia lepidophylla *on medium-textured Fluvisols and Lixisols/Luvisols at San José Llanga during 1992-3. Fuel wood biomass corresponds to specimens >40 cm in height.* Source: Adapted from Barrera (1994).

Years Site was Fallowed	Luvisols/Lixisols		Medium-textured Fluvisols	
	Biomass (kg ha^{-1})	Fuel wood[1] (kg ha^{-1})	Biomass (kg ha^{-1})	Fuel wood (kg ha^{-1})
2-3	168	10	492	79
4-5	196	16	3766	736
6-7	1096	167	--	--
8-10	1697	351	4251	3781
11-15	733	558	7221	5735
>15	--	--	5929	3053

[1]Shrubs harvested for fuel were removed with a pick and harvested material included a significant portion of roots. Barrera (1994) estimated that up to 40% of plant biomass harvested for fuel wood was below-ground material.

factors influence the shift from one site type to another. Garabito's work has been interpreted to suggest that in addition to the short- and medium-term ecosystem dynamics previously discussed, portions of the study area are subject to longer-term changes. He investigated changes in the size structure of salt-tolerant, cushion-plant populations (i.e., *S. pulvinata* and *A. triandrum*) and soil parameters across three ecotones. Results for two ecotones are presented in some detail below, and comments are provided on the third ecotone.

In his investigation of an ecotone between *Salicornia* (*q'auchial*) and *Anthobrium* (*q'otal*) community types, Garabito (1995) focused on the population of *S. pulvinata* plants, a key dominant of the more saline zone. Garabito (1995) found that the proportion of large *S. pulvinata* plants decreased nearer to the abrupt boundary between the two vegetation types (Figure 3.10a). In contrast, the proportion of small *S. pulvinata* plants increased near the abrupt boundary. To illustrate, 4.5-m deep into the *Salicornia* (*q'auchial*) community type *S. pulvinata* plants with a diameter between 41to 60 cm accounted for 22% of the total, while those with diameter between 21 to 40 cm accounted for another 28% of the total. In contrast, just half a meter from the abrupt boundary, 97% of all *S. pulvinata* plants were very small with diameters <21 cm. Taking diameter as a proxy for plant age, Garabito (1995) concluded that the wedge of small plants at the abrupt boundary indicated that *S. pulvinata* was invading the other community type. This large change in the size structure of the *S. pulvinata* population towards predominance by small plants in the vicinity of the boundary was therefore a tell-tale sign of ecotone migration. In this case, the *Salicornia* (*q'auchial*) community would be advancing at the expense of the *Anthobrium* (*q'otal*) community.

Taking his investigation a step further, Garabito (1995) looked at changes in salinity for surface soil and ground water along a transect that straddled the ecotone. He found that the ECe of the surface horizon on the far side of the *Salicornia* (*q'auchial*) community was >3.6 S/m, whereas at the far side of the *Anthobrium* (*q'otal*) community the ECe was <1.7 S/m. Furthermore, the ECe of the ground water was higher (i.e., 2.7 S/m) for the *Salicornia* side of the transect than for the *Anthobrium* side at 2.0 S/m. Finally, Garabito (1995) noted that sur-

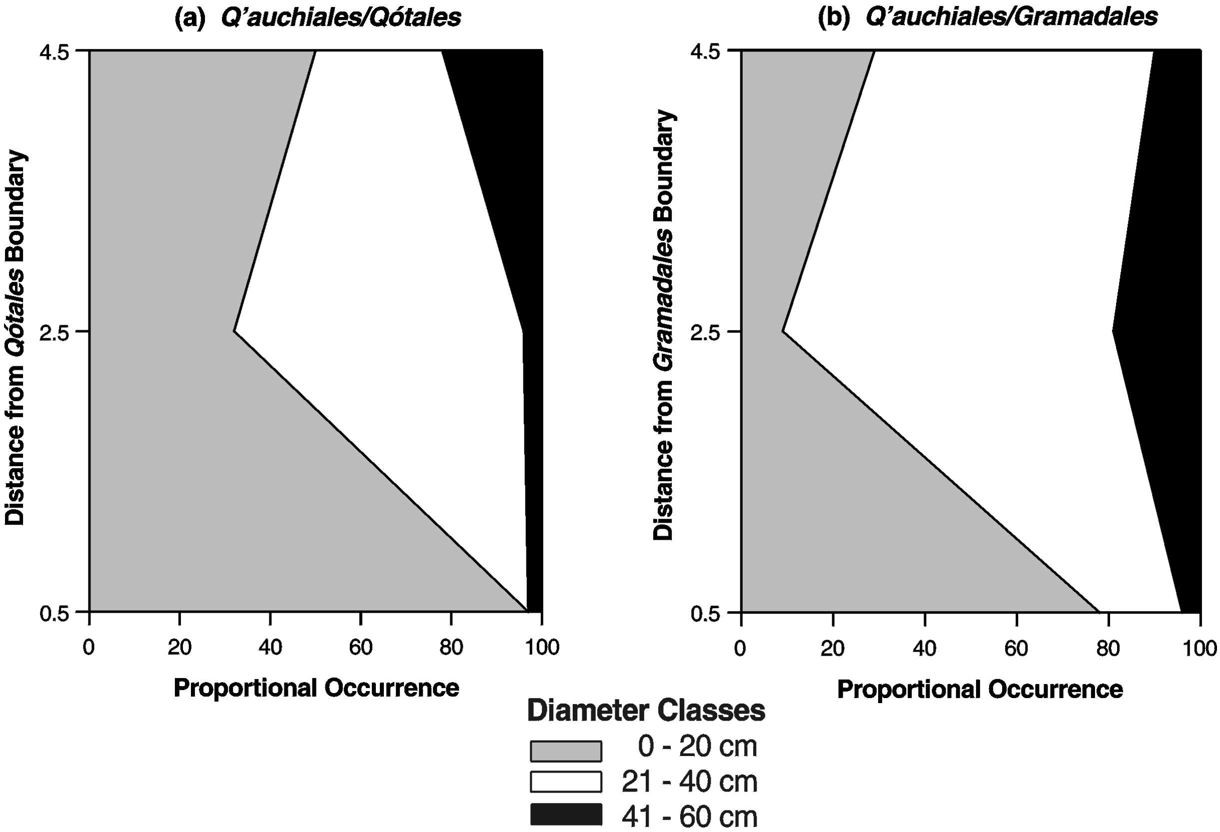


Figure 3.10 (a,b). *Size distribution of populations of the halophyte* Salicornia pulvinata *in two ecotones: (a)* Q'auchial-Q'otal*, an ecotone where a* Salicornia *population met an* Anthobrium *population; and (b)* Q'auchial-Gramadale*, an ecotone where a* Salicornia *population met a short-grass association. In both ecotones the core population of* Salicornia *was associated with more saline substrates than* Anthobrium *or* Distichlis *characteristic of the* gramadale*. "Distance from the boundary" refers to the distance that* Salicornia *individuals were located from the front edge (or mid-point) of the ecotone.* Source: Adapted from data in Garabito (1995)

face soil texture was clay on the *Salicornia* side and sandy-loam on the *Anthobrium* side of the transect.

Based on the premise (and supported by analysis of population-size structure for *Salicornia*) that the ecotone is moving, and the fact that the location of the ecotone is linked to abrupt changes in salinity, Garabito (1995) hypothesised that the spatial distribution of soil salinity is in a state of flux. In this particular case he argued that the area of hyper-saline soils (under a cover of *Salicornia*) is expanding at the expense of the less-saline soil supporting a stand of *Anthobrium*. Because changes in the conductivity of sub-surface water and texture of the soil were associated with changes in salinity of the soil surface, Garabito (1995) speculated that changes in texture and sub-surface water were both driving changes in salinity of the soil surface. His raw data showed that the coarse-textured (sandy-loam) surface horizon on the *Anthobrium* side of the transect had lower salinity than the underlying fine-textured (clay) material in the same location, indicating that the increased salinity of the soil surface where *Salicornia* dominated could have resulted from erosion of the surface layer found with *Anthobrium*.

Garabito (1995) also investigated changes in the size-structure of *S. pulvinata* alongside an abrupt ecotone between a *gramadale* dominated by the grass *D. humilis* and another *q'auchial* having *Salicornia*. Once again he found clear shifts in the size-structure of *S. pulvinata* as the boundary between vegetation types was approached (Figure 3.10b). To illustrate further, 4.5-m deep into the *Salicornia* side the population of *S. pulvinata* consisted predominantly (71%) of plants with diameter >20 cm. On the other hand, only 0.5-m from the gramadale border, 81% of the plants were small and had diameters <21 cm. Garabito (1995) quantified differences in soil salinity on both sides of the boundary as before: on the *Salicornia* side surface ECe was invariably >4.7 S/m, and on the *Distichlis* side it was always <1.7 S/m. In contrast to the first analysis, this time he found no clear differences in other soil parameters between the two vegetation types. Based on the premise that plant size is a proxy for plant age, Garabito (1995) explained the differences in population size structure along the gradient from the ecotone as an indication of ecotone migration, with the *Salicornia* expanding at the expense of the *Distichlis*. Thus the predominance of young (small) *S. pulvinata* plants near the boundary between the two vegetation types.

While Garabito's (1995) studies are exploratory, and alternative hypotheses to ecotone migration may be advanced to explain changes in size structure of *S. pulvinata* described above, the evidence he presented is compelling that ecotones in the salt-affected rangelands of SJL migrate. Evidence he cited also included the overall appearance of ecotones where young, vigorous plants of *S. pulvinata* intermingle with moribund *A. triandrum* and *D. humilis* individuals. We cannot, however, state that the spatial shifts in ecotones stem from human-induced pressures. In fact, a multiple regression analysis undertaken by Garabito (1995) of 126 sample points in which ECe was regressed against several edaphic and hydrologic parameters showed that percentage of silt was the most important predictor of soil surface ECe, followed by the ECw of ground water. Soil salinity at SJL appears to be closely associated with silt-rich parent material often deposited within endoreic lakes, a common geomorphic feature on the Altiplano (see Section 2.3.1: *Regional highlights of physical geography and environment*). In some cases, human pressure may lead to change in the extension of salinised areas by triggering erosion of soil surfaces and exposing saline soil material. At SJL, irrigation with salt-laden water from the Desaguadero River is probably the most important cause of human-induced soil salinity (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). In addition, soil salinity may be increasing due to a slight dessication caused by initiation of a dry climate cycle (see Figure 3.2). If the community is in a dry-phase of a cycle, a decrease in flooding and increase in rainfall variability could contribute to an increasing trend for salinisation (Dr. H. Alzérreca, rangeland ecologist, personal observation).

3.3.3.7 Change in vegetation cover 1972-87

The preceding material dealing with system dynamics has focused on a small-scale level of resolution. The analysis of remotely sensed data by Washington-Allen et al (1998) revealed that: (1) all vegetation types at SJL were impacted by the 1982-3 drought, but more mesic range sites exhibited the least response (see Section 3.3.3.1: Photosynthetic activity of herbaceous vegetation); and (2) approximately 90% of vegetation cover had not changed between 1972 and 1987. This latter finding was interpreted to suggest that livestock grazing was not contributing to resource degradation in terms of change in total vegetation cover, irrespective of vegetation type.

3.3.4 Integration of ecological findings

A summary of various findings for the four key geomorphic units (i.e., alluvial terrace, alluvial fan, deltaic deposits and fluvio-lacustrine plains) is presented in Table 3.6. Collectively these four units comprised 88% of the land area of SJL and probably contributed to virtually all of the productive output for the agropastoral system during the period of observation by the joint IBTA/SR-CRSP project. Diversity in most of the tabulated features is apparent across the four geomorphic units. Each, therefore, is somewhat unique with regards to land cover, hydrology and land-use.

Table 3.7 outlines our interpretation of the likely ecological sustainability for maintaining production from each of the four geomorphic units. This includes apparent environmental trends and events as well as presumed causes of such trends or events. Some of the tabulated information is reported in subsequent chapters of this volume. Many of the causal relationships are hypotheses or speculations based on direct observations by team members and/or opinions of local informants expressed in interviews. The short time frame of field activity for the joint IBTA/SR-CRSP in Bolivia precluded rigorous tests of most causal relationships dealing with ecological sustainability. Many of these relationships may involve decades of complex interactions. Further observation is therefore needed to test hypotheses. A discussion follows that outlines what we see as key issues for each geomorphic unit.

Table 3.6. *Summary of general physical, hydrologic, edaphic, land-cover and land-use features for four key geomorphic units at San José Llanga.*

	Features[1]					
Geomorphic Unit	Percent of Cantón	Common Soil Types	Common Land-Cover	Dominant Sources of Moisture	Common Land Use	Other Remarks
Alluvial Terrace	25	Luvisols Lixisols	Tholares, food crops, forage crops, *kallpas*	Precipitation	Cultivation, grazing, fuel wood	Elevated relict site; non-saline
Alluval Fan	15	Fluvisols	Forage crops, food crops, *tholares, kallpas alfalfares*	Over-flow from ephemeral river; high water table; precipitation	Cultivation, grazing, fuel wood	Site created by river diversion; non-saline
Deltaic Deposits	10	Solonchaks	Food crops, forage crops, *tholares, kallpas*	Precipitation, surface irrigation from perennial saline river	Cultivation, grazing	Relatively new site expanded by irrigation; slightly saline
Fluvio-lacustrine						
Fluvio-lacustrine Plain	38	Solonchaks Fluvisols	*Chilliwares, eriales, gramadales, p'orkeales, q'auchiales, q'otales, yawarales*	Precipitation, high water table; periodic flooding in center	Grazing	Old lake bed; varies from hyper-saline to non-saline

[1]See text for detailed descriptions of features.

Table 3.7. *Summary of apparent environmental trends/events, hypothesized causal agents of trends/events, and implications for sustainability of the agropastoral system as outlined for four key, geomorphic units at San José Llanga.*

Geomorphic Unit	Features		
	Apparent Environmental Trends/Events	Hypothesised Causal Agents of Trends[1]	Implications for System Sustainability
Alluvial Terrace	Perceived gradual decline in crop productivity	Declining rainfall[2], increased use of chemical fertilisers relative to manure, increased use of tractor tillage, shortened fallow period	Negative, but effects mitigated by human emigration and increased market integration
Alluvial Fan	Very gradual expansion of site	Depositional processes of ephemeral river	Positive
Deltaic Deposits	Gradual increases in site salinisation	Use of saline irrigation water from perennial river	Negative over the long-term, but over the short-term irrigation allowed expansion of production
Fluvio-Lacustrine Plain	Shifts in species composition of forages to less-desirable species in the *gramadales* and *p'horkeales*	Chronic, heavy grazing on sacrifice sites nearer to settlements	Slightly negative, as a relatively small area is afflicted and "increaser" species are still utilised. Degraded but stable composition
	Migration of saline soil frontiers	Heavy grazing erodes topsoil and exposes more saline subsoils	Negative, but likely unmanageable
	Large barren patches devoid of vegetation	Past inundation of lake bed	Negative, but likely unmanageable
	Homogenisation of ground water	Proliferation of hand-dug wells perforates formerly isolated cells of saline and non-saline water	Negative, but extent is unclear

[1]Proximal causes.

[2]The strongest hypothesis according to Dr. J. de Queiroz (IBTA/SR-CRSP, personal observations).

3.3.4.1 Sustainability of the alluvial terrace

The finding that may bode most unfavorably for the production system overall is the repeated assertion from local informants that crop productivity is declining on the alluvial terrace (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). Assuming for the purpose of discussion that this is a real phenomenon, possible proximal causes of declines in crop productivity could include factors related to climate and/or management.

The simplest and best hypothesis to explain a decline in crop productivity is a decline in precipitation (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). This is speculative given the limited climate data that were available. Although no long-term trend in mean annual precipitation was apparent during 1952-92, analysis of 7-year running means was interpreted to indicate that the community during the 1990s may have been in the midst of an 11 to 13-year drier-than-average period, which may occur as part of a precipitation cycle (Figure 3.2). Available evidence also suggests that the fluvio-lacustrine plain has endured less flooding in the past 20 years (Section 3.3.2.1: *Geomorphic units*). If a precipitation cycle is occurring, then it is likely that the decline in crop production on the alluvial terrace is also somewhat cyclic and not a long-term trend. Given the link between increased aridity and increased risk of frost (see Section 3.3.1.2: *Air temperature and frost*), crop production could also vary in a cyclic fashion as a result of increased rates of frost damage. A possible cycle involving precipitation/frost and cultivation success has implications for risk management interventions in this agropastoral system (see Chapter 8: *Conclusions and recommendations*).

Management factors may be contributing to a decline in crop productivity, but they probably do not offer as comprehensive an explanation as do periodic swings in precipitation. Possible management factors that could be implicated include changes in soil management. This has several dimensions as discussed below.

Informants commonly reported that many campesinos have shifted from traditional reliance on livestock manure as a crop fertiliser to relatively greater use of bagged chemicals such as urea (Dr. J. de Queiroz and Mr. C. Jetté, IBTA/SR-CRSP, personal observations). This shift has occurred over the past 30 years. Chemical fertilisers became locally available as a result of subsidisation and extension programmes carried out by governmental and non-governmental organisations. Chemical fertilisers are attractive to campensinos because they have been relatively inexpensive, offer short-term boosts for crop production, and are much easier to transport and apply than bulky manure. Disadvantages of chemical fertilisers perceived by campesinos include poor-tasting potatoes, less biomass production of native annuals during subsequent fallow periods, and a long-term hardening of top soil (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). Campesinos at SJL have traditionally transported manure significant distances from corrals to crop lands using donkeys or human labour, which is an arduous process. Although manure markets have recently emerged around SJL and campesinos now regularly export manure to generate cash income, we speculate that this has had less of an effect on decisions to use chemical fertilisers than issues of convenience (see Chapter 4: *Household economy and community dynamics at San José Llanga*). Manure has many attributes as a soil ammendment that can positively influence soil structure, water-holding capacity, erodibility and fertility. This is particularly apparent when dealing with the otherwise structureless, sandy topsoil that characterises the alluvial terrace (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). For example, the OM in sandy soils is tightly linked to an increase in water-holding capacity. Besides contributing nutrients such as nitrogen (N) and phosphorus (P), the OM from manure is probably the most important contributor to the cation-exchange complex in sandy substrates. Manuring may also have a series of positive effects on the nutrient content of croplands by virtue of additive influences dealing with plant successional dynamics. For example, young fallow fields which had been previously fertilised with manure in the cropping rotation showed a much higher production of annual forb biomass compared to fallow fields which had received chemical fertilisers in the cropping rotation (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). Such annual forbs are important for grazing by livestock (Chapter 5: *The grazing livestock of San José Llanga*), and weeds are even harvested for cut-and-carry feeding for tethered cows (Dr. B. Norton, IBTA/SR-CRSP, personal observation). It is unclear whether the surge in forb biomass on previously manured fields is due to the presence of added seed from manure and/or a more favourable growing environment, but regardless it is likely that the higher levels of forb biomass in turn lead to a greater accumulation of detritus and soil OM over time, a factor perhaps more important to long-term site productivity than the original addition of manure (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). Manuring also has implications for reducing erodibility of sandy soils (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observations). Because manure increases the OM content of sandy soils, this favors formation of aggregates which result from binding togther single grains of sand. These aggregates are heavier than single grains and hence more difficult to lift and remove via action of wind or water. The observation that plots treated with chemical fertilisers appear to have top soils which become more hardened over time compared to plots treated with manure may be related to an increased erodibility of soils under the chemical-fertiliser regime. The apparent hardness of such plots could be related to increased exposure of the B horizon with gradual depletion of the A horizon from wind or water erosion (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). In addition, a breakdown of OM over time causes apparent soil hardening because OM particles become smaller (Mr. D. Huber, Utah State University, personal communication). Hardening of the top soil could contribute to reduced infiltration of rainfall.

Increased use of tractor tillage may also have some role in declining crop productivity on the alluvial terrace by virtue of the negative effects that poorly managed tractor tillage could have on erodibility of sandy soils (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). It is speculated, for example, that the more-thorough mixing of surface soil by disc ploughing tends to break down soil structural units to a greater extent than traditional methods using wooden ploughs drawn by oxen. Use of tractors has increased in the past 30 years at SJL. The current situation is that one wealthy individual at SJL owns a tractor, which he then rents out to the community. The owner is also the driver of the tractor. Individual households rent the tractor to till family-owned plots in the cropping matrix. The traditional system of land tenure, which maintains the structurally diverse matrix of tilled and fallow fields, is important in this case because it dictates that tractor tillage not occur on larger spatial scales. If tractor tillage were to occur on larger plots in cases where numerous small plots had been combined, it is conceivable that the alluvial terrace could be more vulnerable to net losses of top soil due to wind erosion. The fact that the driver of the tractor is not the owner of the plots being tilled could raise problems in terms of promoting tillage practices that are expedient rather than careful or conservative in nature (Dr. C. Valdivia, IBTA/SR-CRSP, personal observation). That wind-blown topsoil tends to be redistributed among adjacent plots of fallow and tilled fields, and not lost to the system, is likely important in the long-term sustainability of the alluvial terrace (Barrera 1994).

Management factors include some reports that a shortening of the fallowing period is occurring on the alluvial terrace, especially among households that are “land-poor” (Cala 1994; see Chapter 4: *Household economy and community dynamics at San José Llanga*). This could also be a proximal cause of declining crop yields in some cases. A shortening of the fallow could lower crop production by interfering with nutrient management or pest management.

3.3.4.2 Sustainability of the alluvial fan

Unlike the alluvial terrace, the alluvial fan appears to offer a highly sustainable subsystem. It is expanding due to depositional process (Table 3.7). There were no reports from campesinos of perceived changes in productivity of the alluvial fan. This is fortuitous given the crucial role of cultivated forage production on the alluvial fan in support of emerging small-holder dairying and production of improved sheep (Chapter 4: *Household economy and community dynamics at San José Llanga* and Chapter 5: *The grazing livestock of San José Llanga*). The alluvial fan is a testament to the high and sustained value of irrigation engineering using a source of fresh-water that is wholly controlled within one community. The relative impact of such a development investment for this and similar communities is reviewed in Chapter 8: *Conclusions and recommendations*.

3.3.4.3 Sustainability of the deltaic deposits

Development of the deltaic deposits starting in the mid-1980s with saline irrigation water from the Desaguadero River has granted the campesinos of SJL more than a decade of expanded production in cultivated forages and crops (Table 3.7). The cultivated forage component has allowed more households to become involved in smallholder dairying at SJL (Chapter 4: *Household economy and community dynamics at San José Llanga*). However, the recent appearance of halophytic plants (i.e., *Salicornia* sp.) on some sites suggests that the deltaic deposits are gradually becoming salinised (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). The use of the deltaic deposits therefore appears unsustainable unless a source of fresh irrigation water could be found. Therefore, this is perhaps the best example of how people, in the pursuit of short- or medium-term gains, could mis-manage a production site. Another view could be forwarded, however, namely that given available resources, the campesinos have been clever enough to engineer a significant increase in system productivity for a relatively short period at a site that otherwise may have yielded much less over a much longer time frame.

3.3.4.4 Sustainability of the fluvio-lacustrine plain

Despite the high site-to-site variation within the fluvio-lacustrine plain, our overall impression is that abiotic factors are most crucial in affecting contemporary patterns of vegetation abundance and productivity on this geomorphic unit (Table 3.7). Some clarification follows. The large expanses of the central fluvio-lacustrine plains which are denuded are hypothesised not to be in that condition because of overgrazing, but because of either past flooding regimes (as in the case of the *eriales*) or high endogenous salinity (*q' otales* or *q' auchiales*). Heavy grazing may contribute to effects of salinisation through influences on erosion of top soil. It is also notable, however, that in central Asia heavy grazing has been observed to contribute to salinisation of subirrigated grasslands by reducing water loss via transpiration and hence exacerbating water losses via evaporation. Salts thus move up in the soil profile and are deposited on the surface as part of the evaporative process (Dr. J. Dodd, rangeland ecologist, North Dakota State University, personal communication). The key to understanding why such a large portion of SJL is subjected to these phenomena is landscape position. Being in the centre of the Altiplano, the Cantón of SJL serves as a resource sink for the collection of water and eroded salts from around the region (see Section 2.4.1: *Local environment*). These factors essentially overwhelm most effects of grazing or other aspects of resource use by people on the fluvio-lacustrine plain.

The other non-saline or moderately saline sites nearer to the periphery of the fluvio-lacustrine plains tended to be dominated by perennial grasses (i.e., the *chilliwares*, *yawarales*, g*ramadales or p'horkeales*). These sites largely appeared stable in terms of plant species composition, especially in cases where deeper-rooted perennial species have access to fresh or slightly saline ground water. When clear shifts in the species composition of these plant communities occurs, a major factor to consider is change in the salinity level of soil or ground water. Moving saline ecotones or homogenisation of ground water from proliferation of hand-dug wells could be considered as factors inducing change in such instances. It is also notable that there is probably a relationship between saline ecotones and hydrology (Dr. J. de Queiroz, IBTA/SR-CRSP, personal observation). Saline ecotones may shift because of changes in drainage patterns associated with a precipitation cycle, for example.

Based on our investigations, it is not possible to know with certainty whether or not the contemporary composition or productivity of plant communities like *chilliwares*, *yawarales*, *gramadales* or *p'horkeales* has appreciably changed from that of the past due to chronic and heavy grazing pressure. Unfortunately, there were no ungrazed relict communities to serve as comparative baselines in the Cantón of SJL. There were, however, a few instances where chronic grazing pressure in recent times appeared to have slightly altered grass species composition. Again, *gramadales* and *p'horkeales* sites nearer to human settlements appeared to have reductions in the most palatable species such as *H. muticum*.

As will be reviewed in Chapter 5 (*The grazing livestock of San José Llanga*), the current levels of grazing pressure are indeed high and pervasive. Most of the cantón is grazed each year, and much of the readily accessible grass and forb biomass seems to be removed by grazing. Exploitation of grazing lands at SJL is very efficient. How, then, has massive environmental degradation due to grazing been seemingly avoided at SJL? Again, the landscape position of SJL is probably crucial to this end. The fact that SJL occurs in the bottom of a relatively flat plain between two massive mountain chains means that it is a net collector of nutrients, water and eroded soil. Given a relatively high abundance of such resources for growth, plants are probably endowed with a higher ability to withstand heavy grazing compared to most other Andean locales. The physical system is therefore relatively resilient to effects of grazing and trampling by herbivores. The landscape position confers other fortuitous advantages with regards to natural constraints which facilitate grazing management (Chapter 5: *The grazing livestock of San José Llanga*). For example, water often accumulates on much of the fluvio-lacustrine plains during rainy periods. The resulting water and mud can make much of this area impassable for herders and livestock. One outcome of this pattern is a de facto deferred grazing system on much of the fluvio-lacustrine plain. Sites which are temporarily inaccessible during the rains have plants which are allowed to grow in the absence of grazing. Much of the fluvio-lacustrine plains are actually grazed most heavily in the dry season when the dominant grass vegetation appears senescent and hence likely to be relatively immune from grazing damage in physiological terms. Deferred use of the fluvio-lacustrine plains is also encouraged in some cases by grazing on fallow fields in the cropland matrix. See Chapter 5 (*The grazing livestock of San José Llanga*).

One fundamental flaw in our ecological research was that the project did not establish protected grazing exclosures on important range sites at the start of the project in 1991. The fact that the community of SJL uses virtually all of the available grazing each year made the politics of exclosure establishment problematic. Observation of possible changes in plant community composition and productivity over the ensuing five years would have allowed us to make better-founded conclusions regarding short-term effects of grazing and have insights relevant to the stability and resilience of range plant communities. In light of this problem we can at least make reference to other studies, however, in which sites were protected on the semi-arid puna or in similar eco-regions and describe these findings.

In general, the semi-arid puna is typically regarded as over-grazed (Browman 1974; Cardozo 1979; LeBaron et al 1979; Posnansky 1982; McCorkle 1990). Exotic species such as sheep and cattle have been often implicated in over-grazing due to their particular foraging methods and trampling effects which may impact plants to a higher degree compared to attributes of indigenous camelids (Posnansky 1982). The Altiplano, however, has endured pastoralism of one form or another for up to 7000 years (see Section 2.3.2: *Regional historical highlights*). Plant communities which have persisted over this time frame should be regarded as somewhat adapted to heavy grazing even if their current status is suboptimal in terms of species composition or productivity (Milchunas and Lauenroth 1993). Despite the general concensus that over-grazing is considered to be the norm on the Altiplano, a lack of detailed research leaves many questions unanswered. For example, it is not known the degree to which perceived degraded states of plant communities are stable or unstable. It also is unclear if perceived degraded conditions are reversible or irreversible given appropriate management inputs (Genin and Alzérreca 1995). Evolutionary history is important in considering dynamics of grazing systems.

Results of the few exclosure studies conducted in the semi-arid Altiplano and similar environments often offer equivocal interpretations. Braun (1964) studied the impact of five years of rest from grazing on the composition, density and height of range vegetation at Patacamaya Experiment Station. He found that compared to unprotected range sites, protection from grazing resulted in grass plants that were 50% taller but occurred at a lower density. He also found that a native clover slightly increased in the understory. He observed no other changes. In contrast, work reported in Parker (1974) showed estimates that grazing protection could result in four times greater above-ground biomass yield for range vegetation on the semi-arid Altiplano compared to production under a continuous grazing regime. This work was based on two years of grazing protection using 55 exclosures on seven range sites. In some cases plant biomass yield was 10-times greater than that found on paired plots outside exclosures (Parker 1974). He also noted that species composition changed inside the exclosures to a more palatable and nutritious mix compared to that outside the exclosures. Other work conducted on an eroded site at the Patacamaya Experiment Station revealed that four years of protection from grazing resulted in only slight improvements in biomass production, but species mix became more favourable, compared to adjacent unprotected sites (Freeman et al 1980, cited by Dr. H. Alzérreca, rangeland ecologist, personal communication). Buttolph (1998) has noted that compared to continuously grazed sites, one to three years of grazing protection appears to have resulted in largely negligible differences in productivity and species composition of bofedal and gramadal vegetation at a higher elevation site at Cosapa where camelid production dominated.

In other "cold desert" systems there is an ongoing re-assessment of how grazing affects plant community dynamics. It has been found in the Intermountain West of the USA that removal of livestock from desert grasslands and shrublands has often resulted in no subsequent vegetation change (Smith and Schmutz 1975; Smeins et al. 1976; West et al 1984). In his study of plant dynamics over a 60-year period in a salt-desert shrub community in Utah, Alzérreca (1996) found that while grazing pressure typically reduced plant cover compared to ungrazed locations, major changes in plant species composition and cover usually occurred as a result of shifts in amounts and distribution of annual precipitation.

The results of Smith and Schmutz (1975), Smeins et al (1976), West et al (1984) and Alzérreca (1996) all reveal discrepancies with respect to predictions of traditional range trend and grazing management models. Such traditional models emphasise the role of management control versus abiotic influences. They are based on assumptions of tight, interactive linkages between herbivores and plant communities and relevance of a linear (or Clementsian) succession of plant communities from an early seral stage to a stable climax. In effect, such models predict that a lessening of grazing pressure will result in a linear trajectory towards climax. Conversely, increasing grazing pressure should ultimately result in creation of early seral stages. The possible mis-application of Clementsian principles to arid-land ecology was noted by Westoby et al (1989). In contrast to the traditional concepts, they promoted a "state and transition" model whereby a variety of system states was possible for a particular patch of vegetation. What state the patch happened to be in was determined by coincident events which could include abiotic forces (climate, fire, etc.) and biotic forces (grazing, plant competition, etc.). Accordingly, whether or not the vegetation patch moved from one state to another was postulated to be dependent on the occurrence of one or more coincident events.

Ellis and Swift (1988) and Ellis (1992) echoed similar perspectives with respect to hyper-arid and arid pastoral systems in East Africa. In essence they disputed the idea that grazing was the main determinant of vegetation dynamics in these systems. Their contention was that the high variability in rainfall for a dwarf-shrub savannah in Turkana, Kenya, largely dictated the direction of plant community dynamics. Livestock and people were essentially ineffectual contributors to change in many respects. As climate, not consumers, was postulated to be the main controller of arid-system dynamics, such systems were referred to as "non-equilibrial." In his review of African grazing systems, Dodd (1994) noted that making a clear distinction between equilibrial and non-equilibrial systems could be a problem. Coppock (1993) took some of these arguments a bit further and attempted to identify a gradient of "equilibrial" and "non-equilibrial" systems for East African rangelands. In this analysis he noted that arid African systems receiving <300 mm rainfall per year under hot ambient conditions often supported annual grasslands which are relatively immune from acute grazing pressures; these indeed fit the non-equilibrial paradigm. In contrast, however, cooler semi-arid systems receiving >400 mm of rainfall are often dominated by perennial grasses. The low frequency of drought in these semi-arid systems, in conjunction with clever management by pastoralists, often resulted in high numbers of livestock with the capability to periodically alter vegetation composition and productivity. In the case of southern Ethiopia this included encroachment of woody plants as a result of grass cover being reduced by cattle grazing. This case was referred to as an example of an equilibrial system (Coppock 1993).

The broad issues reviewed in the three preceding paragraphs are relevant to interpreting rangeland dynamics on the fluvio-lacustrine plain of SJL. The equivocal nature of results from other work on the Altiplano by Braun (1964), Parker (1974), Le Baron et al (1979), Freeman et al (1980) and Buttolph (1998) is important and collectively tends to undermine the classical notion that all types of range sites would exhibit dramatic improvements as a result of protection from grazing. This variation in response to protection may be due to differences in degrees of site degradation, site resilience and/or coincidences such as certain precipitation regimes that happened to occur for each trial, etc.

Only the *gramadales* and *p'horkeales* sites nearer to settlements showed shifts in plant species composition as a result of heavy grazing pressure. These sites comprised <20% of the grazing of the fluvio-lacustrine plain (Dr. J. de Queiroz, IBTA/SR-CRSP, personal communication).

We have now set the stage to make some educated speculations about the dynamics of these *gramadales* and *p'horkeales* sites: (1) It is likely that such sites would exhibit some changes in plant composition and productivity if they were protected from grazing; but (2) it is unlikely that these sites would change further unless, for example, there was a long-term shift to a drier or wetter climatic regime. Therefore, these particular *gramadales* and *p'horkeales* sites are probably degraded, but relatively stable, in terms of species composition. Given this situation, it is evident that some sites or patches have been altered by chronic livestock grazing and thus represent one outcome of equilibrial interactions between herbivores and vegetation. The total numbers of livestock also appear generally static on an annual basis. The annual increment of animals produced seems to be effectively marketed (see Chapter 4: *Household economy and community dynamics at San José Llanga* and Chapter 5: *The grazing livestock of San José Llanga*).

3.4 Conclusions

The major questions to be answered by ecological research were: (1) Is the environment at SJL "degraded" in terms of potential to support grazing or cultivation?; (2) if the environment is degraded, which components appear most affected and why?; and (3) what are the roles of people and livestock versus those of natural processes in causing degradation? Before outlining our conclusions it is important to acknowledge the relatively short period of time we were able to make observations at SJL. This makes any conclusions risky.

First, SJL exhibits signs of environmental degradation, but attention to geomorphic units and associated land use is critical to understanding relevant processes. Blanket generalisations for the environment overall are therefore not appropriate or informative. It is also important to note that the unique environmental character of SJL is largely defined by its landscape position as an environmental sink for water, soil and salt. Inference is restricted to similar production systems at the centre of the Altiplano, and has little relevance for systems involving hillside agriculture, for example.

The denuded character of the fluvio-lacustrine plains suggests extreme degradation to the casual observer, especially during dry seasons. Large flocks of grazing sheep and other livestock could easily be interpreted to be the major cause of denudation. Indeed, over hundreds of years of continued use at SJL it is highly probable that grazing has contributed to gradual, negative change in some aspects of plant communities and soils. However, we surmise that the only contemporary degradation attributable to grazing per se is found in *gramadales* and *p'horkeales* sacrifice zones located nearer to settlements. This occurs on <20% of the fluvio-lacustrine plains and thus <8% of the cantón overall. This degradation takes the form of changes in the species composition of forages, which appear relatively stable even under heavy use. It thus seems unlikely that significantly more degradation could occur in these sites under current patterns of precipitation and resource use. Consequently, it appears unlikely that altering stocking rates would have much utility with regards to environmental protection, especially in relation to the marginal returns from range improvements and other social and economic costs (see Chapter 8: *Conclusions and recommendations*). The scenario observed for sacrifice zones of *gramadales* and *p'horkeales* conforms more to the equilibrial theory for plant/herbivore interactions, both in terms of biological dynamics and the associated semi-arid climate.

In contrast to sacrifice zones of *gramadales* and *p'horkeales*, however, the vast majority of acreage on the fluvio-lacustrine plains has been denuded by historical flooding and salinisation processes, for which management by campesinos at SJL plays little or no role. This scenario conforms to the non-equilibrial theory of abiotic processes determining composition and trend of range vegetation by overwhelming effects of grazing management.

There are additional situations where climate and landscape have interacted with grazing to promote maintenance of forage cover. The best example is where temporal patterns of flooding, and thus seasonally limited access for livestock, have encouraged deferred grazing systems on the fluvio-lacustrine plain.

Contemporary threats to sustainable resource use may occur more in the farming dimension of this system rather than in the grazing dimension, consistent with findings in other semi-arid agropastoral situations (Dr. H. Alzérreca, rangeland ecologist, personal observation). The best example of degradation promoted by people at SJL is the irrigation of crops on the deltaic deposits with saline water. Other examples—that remain to be verified—involve potential mis-management of topsoils on the alluvial terrace. While these human-induced effects may indeed be negative, it is important to note that the people have played very positive and creative roles in terms of improving the sustainability of their agroecosystem. The best example of this is the use of environmental engineering to channel non-saline water to create the alluvial fan.

In summary, we conclude that people have played positive and negative roles in modifying the environment at SJL. The livestock currently seem to play a role that is either neutral or slightly negative in most cases. Overall, the contemporary roles of people and livestock seem minor, however, compared to a dominant background of salinisation, flooding and drought that profoundly define system dynamics. A mix of abiotic and biotic controls on environmental trends is the result, which is probably logical for any agroecosystem. In terms of vegetation change in a rangeland context, different patches within the same geomorphic unit exhibited both equilibrial and non-equilibrial features. This undermines the utility of either paradigm for making broad generalisations about the behaviour of this and similar systems.

Intervention concepts to mitigate management-related problems in the environment, as well as recommendation for further research, are found in Chapter 8: *Conclusions and recommendations*.

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