Session XII

Adaptation of root and tuber crop system and mitigation of climate change

Visualization as a tool for assessing the potential climate impact in a potato-based system

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Visual representation could be a useful tool for enhancing information transfer and improving the understanding of complex data. In natural resources management work, visual interactive tools can be developed and applied as virtual laboratories for the communication of different agricultural scenarios and their impact on the environment. A case study on potential impact analysis conducted at Pacayas's watershed, located in Costa Rica, provided data to construct an example of the potential of coupling Geographic Information Systems (GIS) modeling and visualization techniques to facilitate decision making in potato based systems. In this study, the Soil and Water Assessment Tool (SWAT) was used for the prediction of the impact of surface runoff, soil erosion and nutrient losses in the system, based on climatic, topographic, edaphic, land use changes and management factors. Critical visual scenarios were simulated for climate extremes considering a hypothetical increase of the amount of rainfall and land use changes.

Keywords: Visual representation, Pacayas, SWAT, Costa Rica.

Introduction

After more than 30 years of application of computerized simulation in agronomic research (Sinclair and Seligman, 1996), the most important contributions of modeling include the enhancement of management decisions and the aid in education and policy issues concerning agricultural lands (Hammer *et al.*, 2002). These tools not only allow exploring hypothetical scenarios under specific conditions that in other way could be expensive or impossible to recreate, but some of them also give the potential of bringing together farmers and researchers during the development of the model to enhance farm management, among other advantages (Cox, 1996; Hammer *et al.*, 2002).

Nevertheless, some limitations arise in the adoption of complex information systems as aids and decision support systems (DSS) (Kuhlmann and Brodersen, 2001). The development of more user-friendly systems accessible and at low cost for users could contribute to solve some of these disadvantages (Engel *et al.*, 2003). In this context, this work describes an approach to visualize the results of a DSS, SWAT, in a 3D virtual reality environment as a friendly interface for the exploration of critical scenarios in a case study carried out in one of the most important horticultural watersheds of Costa Rica.

Virtual worlds for sharing and communicating research results

For improving the communication of scenarios, in the present work, we used a tool for building virtual worlds called CIPWorlds. Three-dimensional virtual worlds are a type of immersive virtual reality (VR) based on networked desktop platforms. Virtual worlds allow their users to interact in simulated 3D environments that usually mix text-based chat tools with a 3D graphical interface. So these tools provide multi-user synchronous communicative advantages found in chat-type applications such as Multiple User Domains Object Oriented (MOOs) and features of VR immersion through 3D representations (Dickey, 2005).

In this regard, CIPWorlds is an on-line multiuser virtual environment which groups a complex of virtual worlds centered on a primary world. The current virtual worlds found in CIPWorlds are related to the study areas of the project "Desarrollo de Bases para el Análisis de la Vulnerabilidad en Agro-Ecosistemas de Montaña", which receives the financial support of INIA-Spain and is developed by CIP and other institutions of Iberoamerica such as INTA of Costa Rica.

CIPWorlds is based on the Active Worlds client/server environment (Tatum, 2000). Currently, it uses a U1000 server so it allows 50 simultaneous users and a virtual land size of 1,000,000 sq. meters. Users interact with the system through a browser which renders compressed files in Renderware file format. Being a multiuser virtual environment, users can interact through the visual interface making use of an avatar which shows behaviors and expressions based on sequences of animated 3D movements.

In order to run CIPWorlds, the installation of a free plug-in is required. This is accessible over the internet (http://inrm.cip.cgiar.org) and it runs under Microsoft Windows operating system.

A case study

The study area of Plantón-Pacayas is located in the province of Cartago, Costa Rica. This micro watershed has an intervention area of roughly 561 has. It exhibits altitudes between 1720-2900 m.a.s.l. and an annual precipitation of 2227 mm (meteorological station of Pacayas). About 50% is classified as pastures. The land dedicated to crops is about 25%, where potato is one of the most important crops (about 10% of the total area in Plantón-Pacayas) in rotation with other horticultural crops such as broccoli and cauliflower. There is also an important area of forest which covers around 19% of the area (Arroyo *et al.*, 2006).

A particular feature of the area is the slopes patterns, which goes from moderate to highly undulating (i.e. approximately 44% of the area shows slopes of 30-50%, while 31% and 18% of the area show slopes of 15-30% and 50-75%, respectively) (Arroyo *et al.*, 2006).

Developing scenarios of extreme events

The Standardized Precipitation Index (SPI) was used to characterize extreme wet or dry climatic events for the case study. Originally, McKee *et al.* (1993) developed the SPI to quantify precipitation deficits on multiple time scales. The SPI is the transformation of the precipitation time series into a standardized normal distribution (z-distribution). National Drought Mitigation Center (NDMC) classifies SPI in seven categories as seen in Table 1 (Hayes, 2006). In this study we used the SPI_SL_6, program developed by NDMC (2006), to calculate the index with Pacayas' meteorological station rainfall data (monthly data from 1979 to 2006). The classification of the rainfall events for Plantón-Pacayas, over a time series of 28 years are shown in Table 1. Years 1999, 1997 and 1990 were chosen as extremely wet (Yearly SPI = 2.01), moderately wet (Yearly SPI = 1.22) and near normal years (Yearly SPI = 0.01), respectively (Figure 1). Making use of the Soil and Water Assessment Tool (SWAT), these years were used to simulate an extremely wet, moderately wet and near normal scenarios and its possible impacts on soil erosion, surface runoff and nutrient losses. SWAT is a hydrologic free distributed model developed by the USDA-ARS Laboratory developed to study the watershed impact of the management of water, sediment and agricultural chemical yields (Di Luzio *et al.*, 2002). A review of this model is beyond the scope of the present paper but for a complete review see references listed in http://www.brc.tamus.edu/swat.

Table 1. SPI classification and the occurrence percentage in Plantón-Pacayas Subbasin

SPI Values	Category	Occurrence percentage
> 2.0	Extremely wet	3.57
1.5 to 1.99	Very wet	7.14
1.0 to 1.49	Moderately wet	7.14
-0.99 to 0.99	Near normal	64.29
-1.0 to -1.49	Moderately dry	7.14
-1.5 to -1.99	Severely dry	10.71
< -2	Extremely dry	0.00

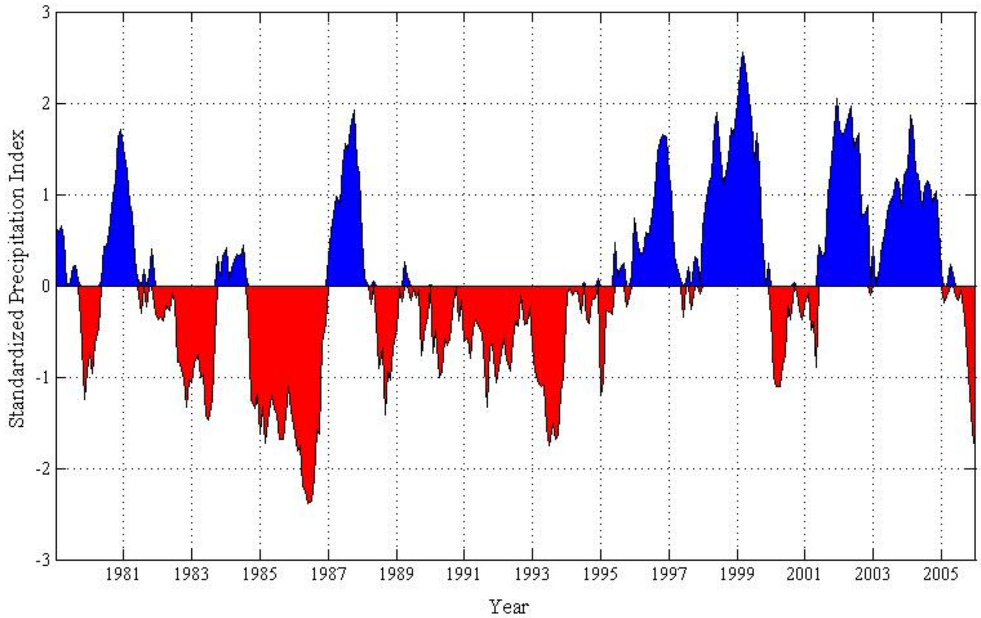
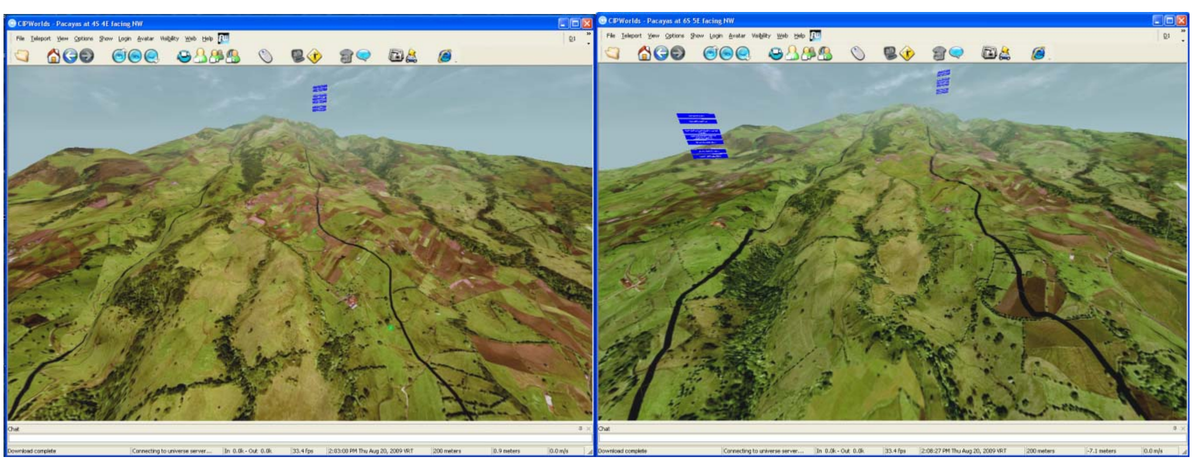


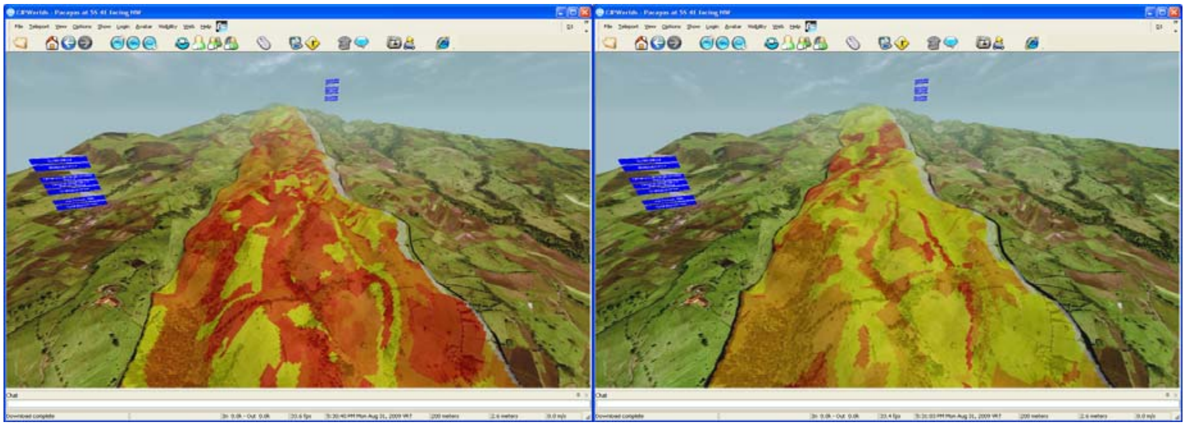
Figure 1. Standardized Precipitation Index (Yearly time-scale)

A 3D model of Plantón-Pacayas was then developed based on a 10 m elevation data obtained from contour lines provided by INTA, Costa Rica and upload to CIPWorlds. The 3D model was texture-mapped with an image from Proyecto Carta 2005 – CENAT, 1:15000. Likewise, a photo-simulation of a hypothetical scenario of an alternative land use was generated replacing crop areas in unsuitable areas for agriculture with pastures (Figure 2). The scenarios generated previously with SWAT were also incorporated as textures upon the 3D model (figure 3). Finally, interactive panels and an assistant bot were programmed for accessing the different layers of information within the 3D environment and panoramic views of several landmarks were linked.



(a) (b)

Figure 2. 3D representation of Plantón-Pacayas. (a) Land use in 2005;
(b) Hypothetical scenario of crop replacement by pastures



(a) (b)

Figure 3. SWAT soil erosion scenarios during an extremely wet year (a) with land use in 2005; and (b) hypothetical scenario of land use replacing crops by pasture

Discussion

One of the first features to be identified in the results of the case study is that Plantón-Pacayas shows high levels of surface runoff, soil erosion and nutrient losses, even in typical years. Furthermore, as expected, erosion was exacerbated during moderate (1997) and extremely wet (1999) years. The negative impact on soil erosion and nutrients loss can be reduced by applying an alternative land use to those areas that should be protected due to their steep slope. In that case, for instance, the results obtained with the SWAT model suggest that the change of horticultural crop areas in Plantón-Pacayas, to a different management option such as pastures reduces the surface runoff, soil erosion and nutrient losses considerably. These results highlight the problem commonly found in tropical highlands where horticultural crops are produced (Bouma et al., 2007). Producing horticultural products in steep slopes demand a comprehensive approach; i.e. tradeoffs between production and environmental deterioration must be included in the economic analysis of policy makers, since the present generation might be consuming the resources of the future generations. It also poses a new challenge for horticultural scientists. Conservation agriculture technologies for steep slopes in tropical highlands are a must, since food should be produced but the damage to the environment should be minimized.

One of the advantages in the use of a 3D representation in this case study was that it allowed visualizing the effect of cultivating steep slopes in Plantón-Pacayas. Figure 3b shows that even in a hypothetical scenario in which horticultural crops are replaced by pastures; there are critical areas that remain affected due to the slope. Moreover, the inclusion of 3D information gives the user new ways of visual analysis since different layers of information can be linked to current views of the area. In addition, the researcher can visit in a virtual way the exact place that the model identifies as a critical area and where high levels of surface runoff, soil erosion and/or nutrient losses are expected.

In the case study, the use of virtual worlds as a tool for 3D representation not only offers new capabilities of visualization, but also provides an interactive environment where immersive experience is highlighted. As a platform for virtual worlds, CIPWorlds also give the tools for scientific collaboration online. Consequently, in the case study, researchers and stakeholders can meet in the virtual representation of Plantón-Pacayas and they can use the tool to analyze together the different scenarios and discuss the course of action in critical events.

Conclusion

The use of virtual worlds for scientific visualization and collaboration provides promising possibilities for increasing the communication and analysis of DSS scenarios. The multi-dimensional data visualization in virtual worlds offers new advantages for visual analyzing complex information and data sets as well as provides the network tools for increasing participation and collaboration among scientists and land managers.

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Tropical root crops: the impact of climate change on future production and utilisation in the South Pacific Island countries

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Abstract

Tropical root crops – cassava, sweet potatoes, aroids, yams and potatoes – are very important staple foods in the world. Around one billion people regularly consume these crops. The world per capita annual consumption of root crops is about 107kg. In the South Pacific Island Countries the per capita annual consumption of tropical root crops is around 200kg. Most of the production and consumption of tropical root crops in the South Pacific Island Countries occurs in subsistence and semi-subsistence settings. Climate change is expected to have a major impact on the world production and consumption of tropical root crops. No where else will the impact of climate change be more significant than in the low-lying island nations of the South Pacific. World renowned climate scientists are predicting the sea level to rise by 1-1.5m by the turn of this century. In countries such as Kiribati and Tuvalu, where most of the people live at elevations of less than 2m above sea level, the rising sea level will be catastrophic for the tropical root crop producers and consumers. In other South Pacific Island Countries which have a significant number of low-lying islands or areas, such as in Fiji, Tonga, Cook Islands, Vanuatu, Niue, and Wallis and Futuna Islands, the rising sea level will also be equally devastating for a large number of tropical root crop producers and consumers.

Keywords: climate change, sea level rise, food security, tropical root crops, world production, South Pacific Island Countries

Climate change and the world root and tuber crop production

For the first time in human history the world is facing significant global warming that is likely to lead to catastrophic effects on world food security. Renowned world climate scientists are predicting that the sea level will rise by 1.1.5m by the turn of this century (Chandra, 2009a,b). This will have devastating consequences for some tropical root crops (TRC) producers and consumers.

The TRC are important staple foods in the world (Table 1). The annual world production of cassava is 228mt, sweet potatoes 126mt, taro 52mt, yams 12mt, and potatoes 322mt. The world root crop production has steadily increased from 688mt in 2001 to 740mt in 2007. TRC are especially important to poor and vulnerable people living in the tropics and sub-tropics who regularly produce and consume TRC in subsistence and semi-subsistence settings. For them any negative impact of global warming will mean even more poverty, hunger and malnutrition.

However climate change's effect on the future of TRC in the world is not only due to sea level rise. Others factors are at play which make TRC even more important than they are today in ensuring world food security and perhaps improving food security in some settings. First, the world cereal production has stabilised at around 2bt and the world's cereal stock has declined from around 116 days supply to around 57 days supply i.e. world cereal food security is declining. Second, world population growth is now outpacing world cereal production growth meaning that cereal consumption per capita is declining. Third, rising incomes in the West are diverting cereal production into animal feed to convert to beef, poultry and pork. Fourth, declining and more variable rainfall in the main cereal production zones is reducing yield and quality. Fifth, diverting food crops such as maize, cassava, oil palm and sugar cane to produce bio-fuels for motor vehicles is further reducing world food security. Sixth, water is becoming a declining and more expensive resource thereby putting additional pressure on non-TRC food production.

Table 1. World Root and Tuber Crop Production (1000t) in 2007

Region	Cassava	Sweet-potatoes	Yams	Taro	Potatoes
Africa	117,888	13,478	50,137	9,506	16,323
North America, Central America, Caribbean	1,438	1,466	533	19	24,958
South America	36,808	1,288	692	9	13,792
Asia	71,808	109,339	237	2,039	135,608
Oceania	196	649	347	376	1,659
Europe	-	79	2	-	129,396
World	**228,138**	**126,299**	**51,948**	**11,949**	**321,736**

Source: FAO Statistics Division 2009.

These factors all point to the increasing importance of TRC for the future world food security. The underpinning factor is that TRC have high efficiency ratios in their production and in their conversion to consumable products surpassed by no other staple food crops in the world.

Tropical root crop production and consumption in the south pacific

TRC are very important staple foods in the South Pacific (Table 2). Papua New Guinea is the largest producer of cassava, sweet potatoes, yams and taro totalling over 1.5mt annually. Other large producers of TRC in the South Pacific are: Fiji, Federated States of Micronesia and Tonga for cassava; Solomon Islands, New Zealand and Tonga for sweet potatoes; Solomon Islands, New Caledonia and Fiji for yams; Solomon Islands, Fiji and Samoa for taro; and Australia, New Zealand and New Caledonia for potatoes. A number of other TRC are important food crops in the South Pacific Island Countries such as *Alocasia* taro in Samoa and Tonga, *Xanthosoma* taro in Fiji and Vanuatu, and a large number of indigenous varieties of yams in Papua New Guinea, Solomon Islands, Vanuatu and Fiji.

Other notable features of Table 2 are: (a) the large mixture of cassava, sweet potatoes, yams, taro, and other root crops consumed within a country which gives some indication of their individual seasonal importance and together their overall importance in providing food security throughout the year, and (b) the relative importance of some TRC over others between the different countries indicating the unique ecological settings within the islands where TRC are grown. In some coral atolls, such as in Kiribati and Tuvalu, the ability to grow cassava, sweet potatoes, potatoes, yams and taro is very difficult because of their meagre soil and little fresh water.

Food security in remote island settings is synonymous with the ability of the people to produce TRC throughout the year. Relative to the rest of the world TRC in the South Pacific Island Countries have much greater food security value because of the absence of other major staple food crops. For this reason the South Pacific Island cultures are intimately entwined with TRC production and consumption. Sweet potatoes, yams and taro have a long and historical significance for the indigenous communities of the South Pacific. Cassava is a relatively recent introduction in the South Pacific, first introduced into Fiji around 1855. Only sweet varieties of cassava were ever introduced.

The population, production and consumption of TRC in the South Pacific are shown in Table 3. A notable feature of Table 3 is the very high reliance placed on TRC as the main source of staple food – 14 countries have an annual per capita consumption rate of over 100kg; 6 countries (Cook Islands, Niue, Papua New Guinea, Solomon Islands, Tonga, and Wallis and Futuna Islands) have an annual per capita consumption rate of over 200kg.

Table 2. South Pacific Root and Tuber Crop Production (t) in 2007

Country	Cassava	Sweet-potatoes	Yams	Taro	Potatoes	Unspec.	Total
American Samoa	100	-	820	9,000	-	-	9,920
Australia	-	4,500	-	-	1,150,000	-	1,154,500
Cook Islands	1,500	700	-	-	-	2,500	4,700
Fiji	34,500	6,000	5,200	38,000	80	3,700	87,480
Federated States of Micronesia	12,000	3,200	-	-	-	-	15,200
French Polynesia	4,300	-	-	-	900	5,250	10,450
Guam	-	130	-	-	-	2,500	2,630
Kiribati	-	-	-	2,200	-	8,200	10,400
NewCaledonia	3,200	3,200	12,500	400	2,400	-	21,700
New Zealand	-	18,500	-	-	505,000	-	523,500
Niue	50	260	130	3,300	-	-	3,740
Papua New Guinea	125,000	520,000	290,000	260,000	900	306,000	1,501,900
Samoa	370	-	2,700	17,600	-	3,000	23,670
Solomon Islands	2,500	86,000	30,000	40,000	-	-	158,500
Tokelau	-	-	-	-	-	300	300
Tonga	9,700	6,800	4,700	3,800	-	2,150	27,150
Tuvalu	-	-	-	-	-	150	150
Vanuatu	-	-	-	-	-	43,000	43,000
Wallis and Futuna Islands	2,550	-	560	1,700	-	1,100	5,910

Source: FAO Statistics Division 2009.

Table 3. Population, Production and Consumption of Tropical Root and Tuber Crops in the South Pacific in 2007

Country	Population	Production (t)	Consumption (kg/capita)
American Samoa	63,450	9,920	156
Australia	21,153,000	1,154,500	55
Cook Islands	21,100	4,700	223
Fiji	840,250	87,480	104
Federated States of Micronesia	106,150	15,200	143
French Polynesia	251,000	10,450	42
Guam	174,500	2,630	15
Kiribati	92,000	10,400	113
New Caledonia	230,000	21,700	94
New Zealand	4,150,000	523,500	126
Niue	1,420	3,740	2634(a)
Papua New Guinea	5,910,000	1,501,900	254
Samoa	161,100	23,670	147
Solomon Islands	531,500	158,500	298
Tokelau	1,580	300	190
Tonga	105,000	27,150	259
Tuvalu	10,000	150	15
Vanuatu	220,500	43,000	195
Wallis and Futuna Islands	15,000	5,910	394

Source: FAO Statistics Division 2009 and other sources.
(a) An anomaly due to a very large share of the production being exported.

Effect of sea level rise on tropical root crop producers and consumers in the south pacific island countries

A significant proportion of TRC production in the South Pacific Island Countries is produced on land barely 3-5m above sea level consisting of coral atolls, river deltas and coastal strips of land where subsistence and semi-subsistence agriculture is practised. Living close to the sea has been important for most South Pacific islanders for a very long time; as it enables them to do subsistence and semi-subsistence fishing which is a key source of animal protein. It also enables other important food crops to be grown with TRC such as coconuts, breadfruit, pandanus and bananas to supplement the diet.

Because of the South Pacific islanders' preference to live by the sea, a large number of countries in the South Pacific are vulnerable to even a small rise in sea level. For example around 400,000 people in the South Pacific live on elevations less than 2m above sea level. Most of these people live on low-lying coral atolls. Everyone in Kiribati (92,000 people) and Tuvalu (11,000 people) live on coral atolls, with maximum elevations of 4m and 3m above sea level respectively.

Other countries in the South Pacific that have a significant number of inhabited coral atolls and low-lying areas threatened by rising sea level are in Fiji, Tonga, Cook Islands, Vanuatu, Niue, Federated States of Micronesia, American Samoa, Tokelau, and Wallis and Futuna Islands. All these countries are important producers and consumers of TRC.

The future of the South Pacific TRC producers and consumers living on low-lying coral atolls and other low-lying areas is bleak. Scientists predict that within 50 years most of these low-lying areas will become inhospitable, with seas inundating the main production zones, thereby unable to support a sustainable population as at present. The only alternative left for the islanders would be to migrate to other nations.

The special case of Kiribati and Tuvalu

The people of Kiribati and Tuvalu are Micronesians. They have been living in these low-lying coral atolls for around 3,000 years, most likely having originated from the West from the Asian mainland. The main TRC produced and consumed in Kiribati and Tuvalu is the giant swamp taro (*Cyrtosperma chamissonis*); no other TRC can be grown as successfully. Giant swamp taro has been grown in Kiribati and Tuvalu since 1000-1200AD. There is now a rich folklore centred around its production and consumption.

Giant swamp taro is grown in dugout coral pits which enable fresh water for plant growth to be drawn in from adjacent water lens; there are no running streams in Kiribati or Tuvalu. The soil is very shallow, alkaline coralline material. Plant organic matter in the form of dry coconut, breadfruit and pandanus leaves is used as mulch around the base of the giant swamp taro plant. Used tinned fish and meat cans are sometimes put around the plants to increase iron content of the soil which has severe iron deficiency. Giant swamp taro usually takes 18 months to 2 years to grow to harvestable size. Annual per capita consumption of giant swamp taro in Kiribati and Tuvalu is around 81kg. Other TRC consumption is around 21kg per capita.

Predictions are that within 30-50 years the people of Kiribati and Tuvalu will have to move to other nations as their land will become inhospitable through rising sea level.

Other projected impacts of climate change on tropical root crop producers and consumers in the South Pacific Island countries

Scientists predict that global warming will not only lead to rising sea level but will also cause: (a) greater variability in rainfall patterns, (b) more intense tropical cyclones, and (c) changes in the onset of El Nino Southern Oscillation.

For some TRC producers and consumers in the South Pacific Island Countries the projected effects of climate change are likely to be challenging because the countries: (a) are surrounded by large expanses of ocean, (b) have little natural resources, (c) are prone to natural disasters such as hurricanes and tsunamis, (d) are relatively isolated making attaining food security difficult, (e) are small, fragile economies highly dependent on aid, (f) have rapidly increasing populations mainly due to high fertility, declining infant mortality and increasing life expectancy, and (g) have rapid urbanisation thereby reducing subsistence and semi-subsistence life-style food security.

In this context it is sad state of affairs that the tiny South Pacific Island Countries, which collectively account for a mere 0.0012 per cent of the global greenhouse gas emissions, are the most vulnerable in the world through global warming (Australian Bureau of Meteorology, 2007).

Conclusions

TRCs are very important staple foods in the world. In the South Pacific Island Countries the per capita annual consumption of TRC is around 200kg. No where else in the world will the impact of climate change be more significant than in the low-lying island nations of the South Pacific. World renowned climate scientists are predicting the sea level to rise by 1-1.5m by the turn of this century. In countries such as Kiribati and Tuvalu, where most of the people live at elevations of less than 2m above sea level, the rising sea level will be catastrophic for TRC producers and consumers. In other South Pacific Island Countries which have a significant number of low-lying islands or areas, such as in Fiji, Tonga, Cook Islands, Vanuatu, Niue, Federated States of Micronesia, American Samoa, Tokelau, and Wallis and Futuna Islands, the rising sea level will also be equally devastating for a large number of TRC producers and consumers.

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Ex ante assessment of climate change adaptation strategies in resource-poor countries: study cases from East Africa

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Abstract

Sub-Saharan Africa (SSA) is predicted to experience considerable negative impacts of climate change. The IPCC Fourth Assessment emphasizes that adaptation strategies are essential. Addressing adaptation in the context of small-scale, semi-subsistence agriculture raises special challenges. An important constraint is that data demands are high, because site-specific bio-physical and economic data are required. The development of relatively simple methods for ex ante evaluation of adaptation at the household and system levels is therefore needed. We test a new approach to ex ante impact assessment that produces site-specific results that can also be aggregated for regional analysis. The methodology uses the kinds of data that are more often available in resource-poor countries. The stochastic approach integrates socio-economic and bio-physical data on farmers' land allocation, production, input and output use. Spatially heterogeneous characteristics of the agricultural system regarding resources and productivity are analyzed and compared for both current and predicted future climate. Possible adaptation strategies are then assessed for their capability to reduce the adverse effects of climate change. We apply the methodology to some contrasting study areas in East Africa. After characterizing the current system with actual climate data, the effects of a perturbed climate are analyzed and a variety of adaptation strategies tested. Despite the limitations, the new approach offers a flexible framework for evaluating adaptation strategies using scarce data of resource-poor countries in SSA and other parts of the world. It allows a rapid integrative analysis for timely advice to policymakers and for exploration of technology and policy options.

Keywords: adaptation, climate change, **s**weetpotato, potato, East Africa, impact assessment.

Introduction

The changing climate is exacerbating existing vulnerabilities of the poorest people who depend on semi-subsistence agriculture for their survival (Slingo *et al.*, 2005; IPCC, 2007). Sub-Saharan Africa (SSA) in particular is predicted to experience considerable negative impacts of climate change (e.g., Thornton *et al.*, 2006). The IPCC Fourth Assessment emphasizes that adaptation strategies are essential and these must be developed within the broader economic development policy context (IPCC, 2007). Addressing adaptation in the context of small-scale, semi-subsistence agriculture in SSA raises special challenges that cannot be addressed adequately by the approaches taken thus far in most studies (Adger, 2003). Most of the existing research has focused on impacts of climate change and adaptation to climate change in the agricultures of industrialized countries. In the relatively few studies conducted in Africa, agricultural research has either focused on individual crops (e.g., Hijmans, 2003; Jones and Thornton, 2003), has used aggregated data and models (e.g., Winters *et al.*, 1999; Mendelsohn *et al.*, 2000), or used statistical analysis too general to be useful for site-specific adaptation strategies (e.g., Kurukulasuriya and Mendelsohn, 2006). Some recent studies at the sub-continental scale for Africa indicate the importance of assessing the effects of climate change and possible adaptation strategies at the agricultural system and/or household level, rather than focusing on aggregated results that hide a large amount of variability (Burke *et al.*, 2009; Thornton *et al.*, 2009). One of the important constraints to carrying out this type of research at this scale level is that the data demands are generally high, because site-specific bio-physical and economic data are required, typically obtained from costly multi-year farm-level surveys. At the spatial resolution required, another drawback is that projections of climate change and simulations of the effects on crop and livestock productivity come with a high degree of variability and associated uncertainties depending on the climate models and methodologies used. The development and application of relatively simple and reliable enough methods for *ex ante* evaluation of adaptation strategies at the household and agricultural system levels are needed to provide timely assessments of the potential impacts in the context of climate change.

Methods

This paper summarizes and applies a new approach to *ex ante* impact assessment that produces locally useful, site-specific results that can also be aggregated for regional policy analysis. The methodology makes use of the kinds of data that are more often available, especially in resource-poor countries. The stochastic approach uses and integrates available socio-economic and bio-physical data on farmers' land use allocation, production and input and output use. Spatially heterogeneous characteristics of the agricultural system regarding resources and productivity are analyzed and compared for both current climate conditions and projected climate changes. A variety of possible adaptation strategies is then assessed for their capability to overcome or reduce the adverse effects of climate change (or to exploit positive projections). A static expected profit maximization model is used to characterize the opportunity cost of adaptation (Antle and Valdivia, 2006). The model can represent the impact of climate change as the "compensating variation", i.e., the loss in income that producers experience relative to the base climate scenario. Alternatively, the economic feasibility of adoption of a certain adaptation strategy or policy can be expressed (Claessens *et al.*, 2009). Details of the methodology can be found in Antle and Valdivia (2006) and Claessens *et al.* (2009). For the climate change projections we used data from the IPCC Fourth Assessment report (2007) and downscaling techniques as described in Thornton *et al.*, 2009. Crop growth simulation models as currently implemented in version 4.0 of the Decision Support System for Agrotechnology Transfer (DSSAT, ICASA, 2007) were used. For the livestock component of the Vihiga system (see next section), an empirical equation relating changes in feed quality with milk yield was used (Claessens *et al.*, 2009). The inclusion of the RUMINANT livestock model (e.g., Thornton and Herrero, 2001) in the methodology is foreseen.

Results and discussion

We apply the methodology to the mixed crop-livestock systems of Vihiga district in western Kenya and the Machakos area in eastern Kenya (Table 1). After characterizing the current agricultural system with current climate data, the effects of a perturbed climate on bio-physical and economic indicators are analyzed and a variety of adaptation strategies (agricultural technologies in this case) are tested.

Table 1. General setting of study areas

Study area	Altitude	Temperature	Precipitation	Crops
Vihiga	1300-1500 m	14°-32°C	1800-2000 mm	maize, beans, Napier grass, sweetpotato
Machakos	400-2100 m	15°-25°C	500-1300 mm	maize, beans, sorghum, vegetables, fruits, cassava

For the Machakos area, the effects of projected climate change to 2050 on farmers' income are shown in Figure 1. More than 80% of the farmers are expected to have losses as a result of climate change. Two adaptation strategies (an improved, heat tolerant maize variety and the introduction of sweetpotato in the area) are explored. Both technologies are predicted to only partly offset the adverse effects of climate change. In contrast to the Machakos area, Vihiga and the highlands of western Kenya in general are predicted to possibly benefit from climate change in terms of crop productivity. A 35% yield increase from the maize-beans sub-system was simulated and dual-purpose sweetpotato was treated as an essentially new crop with varying (but realistic, on-farm) yields. Figure 2 shows that, without climate change, between 52 and 85% of the farmers would economically benefit from adoption of dual-purpose sweetpotato, depending on average yield and assumptions made (Claessens *et al.*, 2009). The effects of climate change on the results of the analysis are negligible. Vihiga could be an example of an area where farmers can possible benefit from climate change whereby, at the regional scale level, adverse effects on crop productivity elsewhere could be offset.

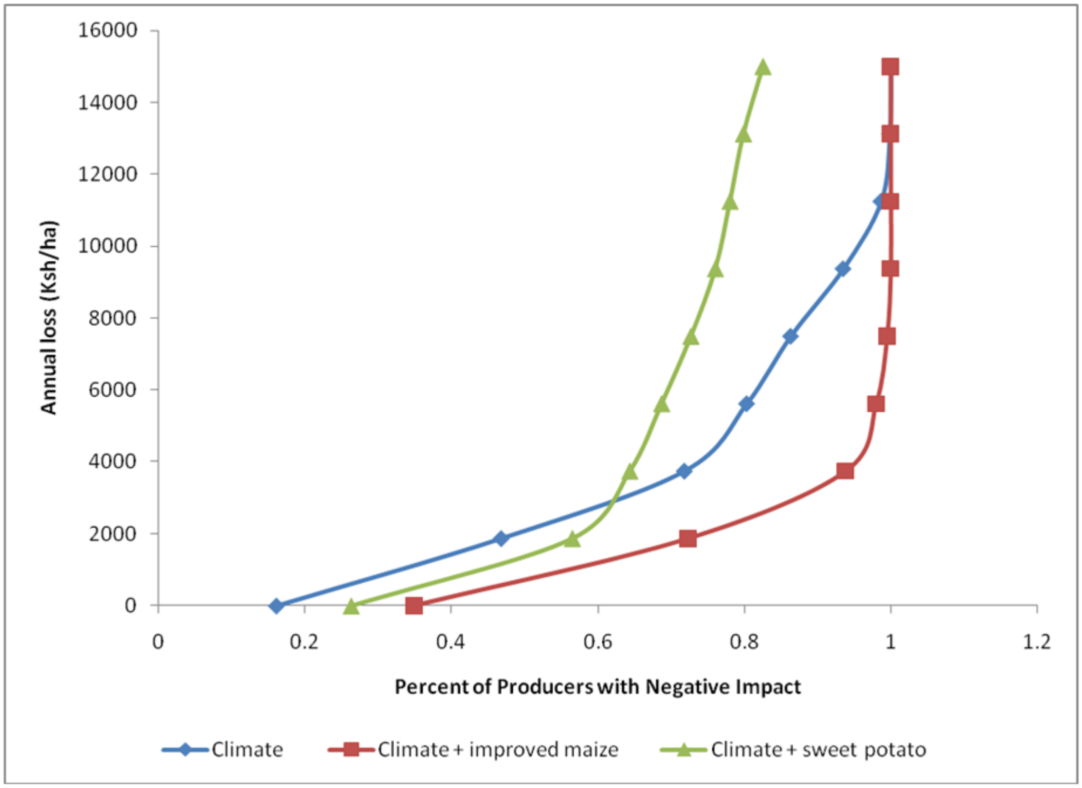

Figure 1. Impact of climate change and adaptation strategies on farmers in Machakos, Kenya

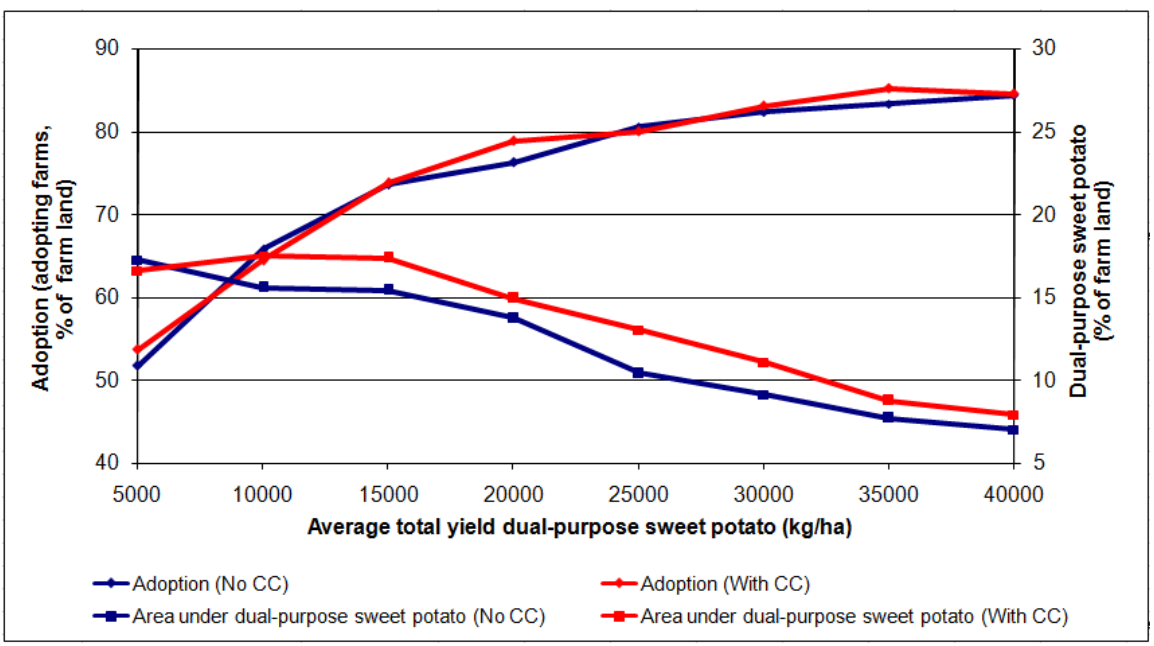

Figure 2. Adoption of dual-purpose sweetpotato in Vihiga and the effects of climate change

Conclusion

The two contrasting examples presented in this paper clearly call for the need of assessing climate change adaptation strategies at the agricultural system and household levels. Despite the limitations, the methodology presented in this paper, offers a flexible framework for evaluating adaptation strategies in the context of climate change using scarce data of resource-poor countries in SSA and other parts of the world. It allows a rapid integrative analysis for timely advice to policymakers, extension workers and for exploration of technology and policy options.

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Utilization of high-resolution satellite images to improve the statistics of sweetpotato cultivated area in the District of Kumi in Uganda

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Abstract

Sweet potato (SP) is a staple crop for poor households in rural Africa. Nevertheless, the area under SP and its distribution is difficult to assess due to the existence of very small plots ubiquitously distributed, including the roadsides. Multispectral (XS) and panchromatic (P) SPOT satellite images -registered on May 6 and October 15, 2006, with a resolution of 10 and 5 m, respectively- were used to evaluate the area under SP in the Ugandan Kumi district. The methodology was based on the use of high-resolution SPOT imagery, complemented with field radiometric evaluations using the Handheld ASD Field Spec Spectroradiometer. An unsupervised classification was initially carried out using clustering algorithms for assessing land use variability and plant coverage. Subsequently, a supervised classification was conducted. Spectral patterns recorded in the fields were used to generate a Maximum Likelihood Classifier for assessing the area cultivated with SP, which was further ground-truthed during May and November 2006. The cumulative area under SP for both cropping seasons, gave a total of 44,620 ha. No official statistics were available for 2006; however, the official data for the period 1992 – 2003 ranged from 21,000 to 28,000 ha. Projecting the linear trend from the statistics to 2006 gave a value of less than 30,000 ha which represented only 67 % of the registered area in our study. The results suggest a significant underestimation of the area planted with SP in Kumi, which is probably the case for most countries in Africa.

Keywords: Remote sensing, statistics, sweetpotato, Uganda.

Introduction

Crop statistics information is important for the implementation of research and development projects. Agricultural statistics are utilized for decision-making with regard to the planning of development activities to benefit the populations that occupy a target region. FAO (1999, 2003) points out that in order to plan agricultural research and rural development strategies it is absolutely necessary to have an information system that provides reliable data on the total area cultivated under a specific crop, the size of the production units, the agro-ecological areas where the crops are found, the soil and climate characteristics, the socioeconomic condition of the producers and the cropping schedule, among others.

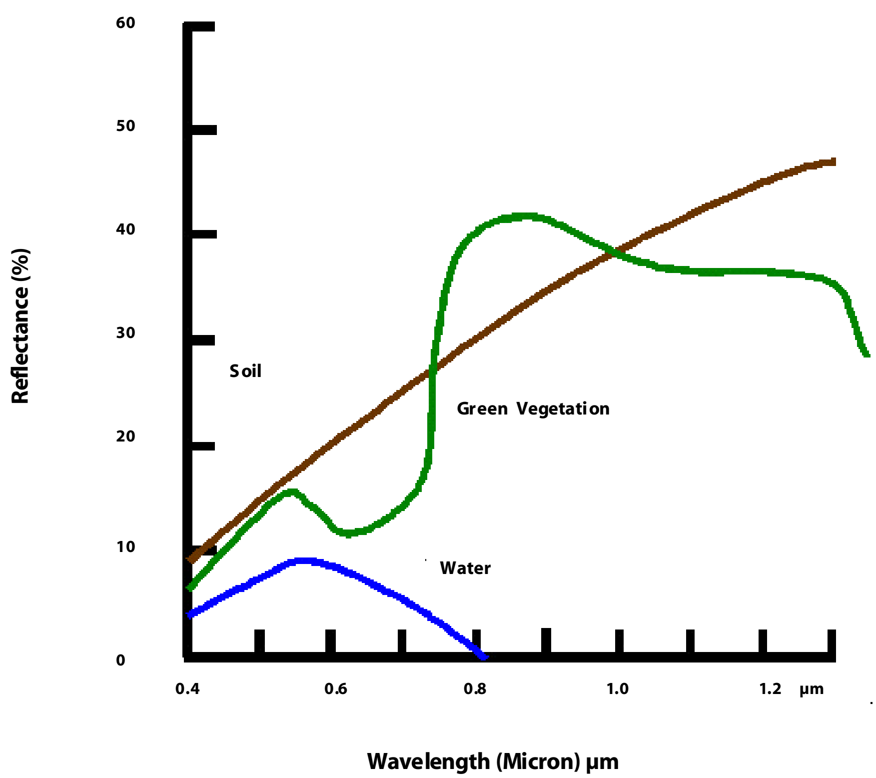
There are reasons to believe that current statistics on SP extensions cultivated in Africa do not bear a relation to the actual cultivated area. This reasonable doubt is based on the fact that crop statistics related to small producers, are obtained through field sampling and survey techniques that have some limitations. It is hypothesized that the accuracy of SP statistics can be improved with the introduction of remotely sensed data. The objective of this research was to quantify the area under sweet potato in the Ugandan Kumi district

Physical basis of the discrimination between crops

When radiant energy strikes on any material an interaction occurs between them. Thus, the crops interact with solar radiation. A fraction of incoming radiation is absorbed by the plant pigments Chlorophyll, Carotenoids, Xanthophylls and others, another fraction is transmitted toward the bottom of the canopy and the soil, and a further fraction is reflected back to space (Colwell *et al.,* 1983).

The property that is utilized to obtain information on the interaction between the radiant energy and the objects on the surface of the earth is the reflectance, which is the ratio of the energy reflected in a given wavelength to the incoming energy (Lillesand and Kiefer, 1994). The vegetation, the soil, and the water bodies have distinct spectral patterns of reflectance, which makes it possible to differentiate them (Figure 1). Furthermore, each plant canopy has distinct spectral patterns or spectral signatures (Jensen, 1996; Richards, 1993) that are utilized to distinguish them from other plant coverage and land uses, making it possible to quantify their respective areas. This differentiation between plant covers is based on the radiometric differentiation of the classes being considered (Lemoine and Kidd, 1998) Sweet potato can be differentiated both in the range of the visible spectrum, where it shows a low reflectance attributed to the pigmentation of the foliage and the total soil coverage, and in the near infrared where the reflectance is very high. This high reflectance of sweet potato fields in the near infrared spectrum is instrumental in distinguishing it from other crops.

To accommodate the diversity of plot sizes, crop species, varieties, clones and cropping systems found in a region, satellite products at an appropriate level of spatial, spectral and time resolutions are needed. These products are used for different purposes in constructing statistics in developed countries (e.g. Allen *et al.*, 2002; Csornai *et al.,* 2006; Fang, 1998; Hanuschak and Delince, 2004; MacDonald and Hall, 1980; and Roller and Colwell, 1986). In developing countries, higher resolution imageries are needed due to field sizes.



Source: http://landsat.usgs.gov/resources/remote_sensing/remote_sensing_applications.php

Figure 1. Spectral patterns of the vegetation, soils and water

Materials and methods

The district of Kumi, located in the northeast of Uganda at latitude 1º 29’15” N and longitude 33º 55’ 58” E, was chosen as a pilot site for the presence of sweet potato cropping fields. This district has an area of 2,848 km^2, a population of 388,015 inhabitants, and a population density of 136.24 inhab./km^2 that is higher than the national average. Most of the population (97.8%) lives in the rural area. Two areas were stratified as a function of annual precipitation. In the dry area there is limited cultivated land, mostly used for drought tolerant crops such as millet and sorghum and some sweet potato. The moist area has much more cultivated land with crops such as sweet potato, peanut, corn, manioc, Chinese beans, and other species

Material and equipment

- Cartographic material
- Multispectral (XS) and panchromatic (P) images from the SPOT satellite. , captured on May 6, 2006 (Figure 4) and on October 15, 2006, respectively.
- Handheld ASD FieldSpec Spectroradiometer
- Magellan Platinum Global Positioning System
- Laptop Dell Inspiron 600 m
- Canon Digital Camera
- Environment for Visualizing Images (ENVI) v. 4.1 Software

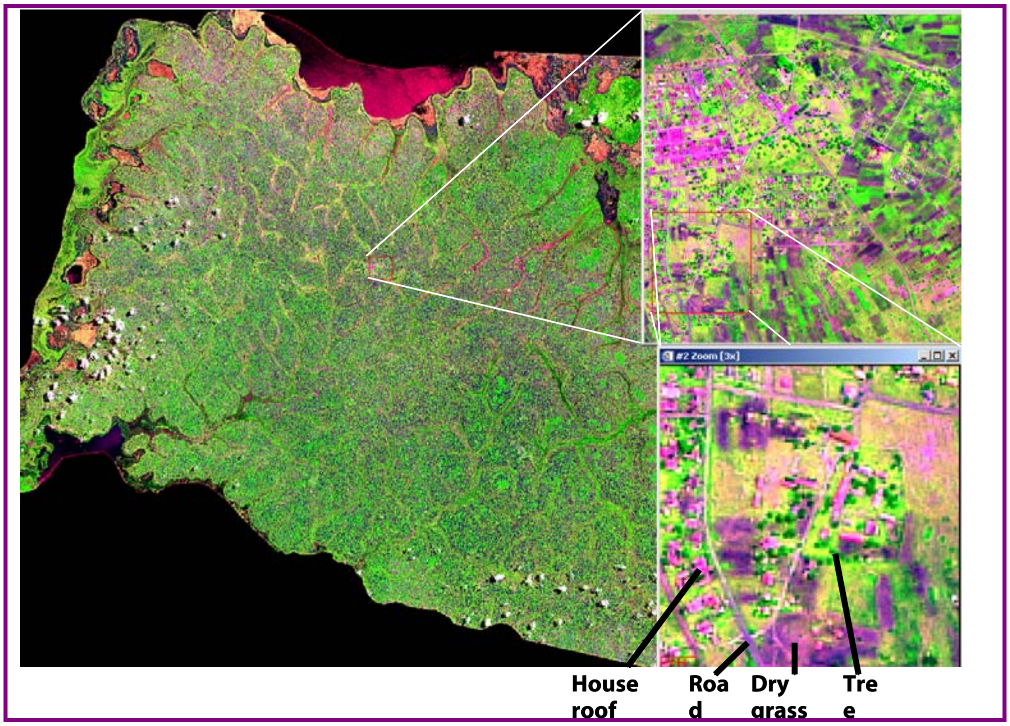
Methodology

Multispectral (XS) and panchromatic (P) SPOT satellite images -registered on May 6 and October 15, 2006, respectively- were used to evaluate the area under SP in the Ugandan Kumi district. (Table 1) (Figure 2). The initial spatial resolution in the multispectral scene was 10 m and the panchromatic band with a 5 m resolution was used for resampling the scene to this resolution. Since the photogrammetric chart for the geometric correction was not available, the requested scenes were corrected with the parameters of navigation of the SPOT 5 satellite.

Table 1. Characteristics of the Sensors, and resolution of the satellite SPOT 5

Sensors	Electromagnetic spectrum	Pixels size	Spectral bands
SPOT 5	Panchromatic B1 : green B2 : red B3 : near-infra-red B4 : short-wave infrared (SWIR)	2.5 m or 5 m 10 m 10 m 10 m 20 m	0.48 – 0.71 μm 0.50 – 0.59 μm 0.61 – 0.68 μm 0.78 – 0.89 μm 1.58 – 1.75 μm

Source: www.spotimage.com



Source: SPOT Image

Figure 2. SPOT image of Kumi

The methodology was based on the use of high-resolution SPOT imagery, complemented with field radiometric evaluations using the Handheld ASD Field Spec Spectroradiometer. An unsupervised classification was initially carried out using clustering algorithms for assessing land use variability and plant coverage. Subsequently, a supervised classification was conducted. Spectral patterns recorded in the fields were used to generate a Maximum Likelihood Classifier for assessing the area cultivated with SP, which was further ground-truthed during May and November, 2006 (Zorogastúa *et al.*, 2007)

Results and discussion

Figure 3 shows the different spectral patterns of the main crops and land uses in Kumi. Sweet potato can be differentiated both in the range of the visible spectrum, where it shows a low reflectance attributed to the pigmentation of the foliage and the total soil coverage, and in the near infrared where the reflectance is very high. This high reflectance of sweet potato fields in the near infrared spectrum has been instrumental in distinguishing it from other crops.

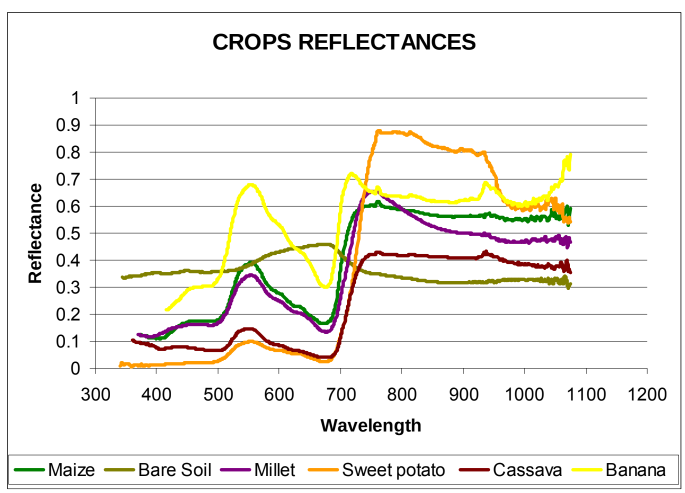
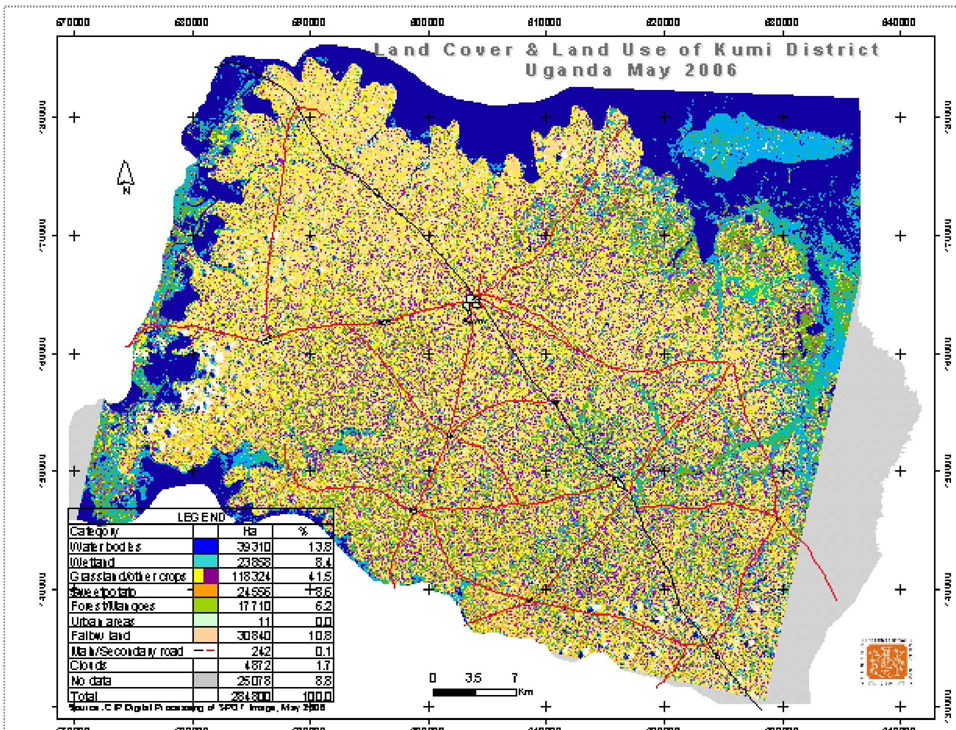


Figure 3. Spectral patterns of the main crops and land uses in Kumi

Figure 4 is the supervised classification carried out with the May 2006 image. It shows that most of the sweet potato fields were located in moist areas while the drier areas were primarily covered by grasses. For ease of reading, the legend of Figure 5 is represented in Table 2. The table shows that sweet potato covered 24,556 ha on the date the satellite image was captured. This area, representing 8.6% of the area of the district, corresponds to the sweet potato crop in the first growing season only. On the other hand, the satellite image captured in October 2006 (Figure 5), processed and ground truthed with the same methods as the other image, shows that sweet potato covered 20,064 ha, or 7% of the area of the district. It appears that this decreased cropping area observed in the second season was due to abnormally delayed rains. Adding up the sweet potato cropping areas observed in the images from the two cropping seasons, the yearly total for 2006 amounts to 44,620 ha. However, the more recent official data from the Department of Statistics of Uganda (Figure 6), point out that in the whole year of 2003 the area cultivated with sweet potato in Kumi was 28,000 ha. Assuming that this estimation remains approximately constant for the following years, including 2006, our remote sensing data suggests that the official statistics record just the 67% of the sweet potato cropping area in Kumi district. In years with normal precipitation, the shortage of the official data would be even greater. If the proportion holds true for other areas, the total area of sweet potato in Uganda might well exceed 1 M ha.



Source: CIP, NRM Geospatial Analysis Laboratory, based on a SPOT scene of May 6, 2006

Figure 4. Classified SPOT Image of the Kumi district, May 2006

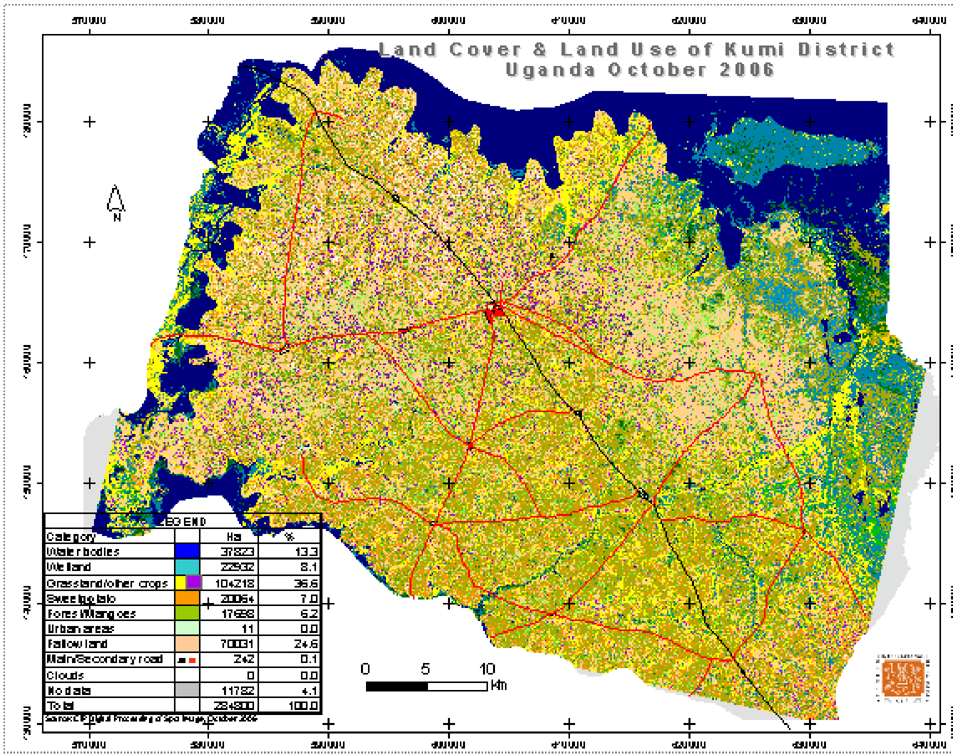
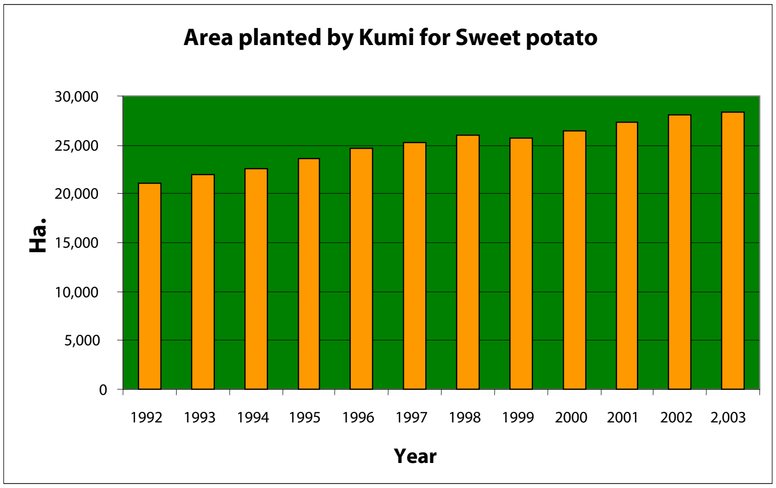


Figure 5. Classified SPOT Image of the Kumi district, October 2006

Table 2. Area covered by different land use and plant cover categories, May and October 2006

LEGEND					
Category		May-06		Oct-06	
		Ha	%	Ha	%
Water bodies		39310	13.8	37823	13.3
Wetland		23858	8.4	22932	8.1
Grassland/other crops		118324	41.5	104218	36.6
Sweetpotato		24556	8.6	20064	7.0
Forest/Mangoes		17710	6.2	17698	6.2
Urban areas		11	0.0	11	0.0
Fallow land		30840	10.8	70031	24.6
Main/Secondary road	.--/	242	0.1	242	0.1
Clouds		4872	1.7	0	0.0
No data		25078	8.8	11782	4.1
Total		284800	100.0	284800	100.0



Source: Uganda Bureau of Statistics (UBOS)

Figure 6. Sweet potato cropping area en the Kumi District according To official statistics of Uganda

Conclusions

The radiometric evaluation and processing of the SPOT scenes of the district of Kumi in Uganda have made it possible to determine that the sweet potato foliage has a distinct spectral pattern defined by a low reflectance in the visible range of the spectrum and a high reflectance in the near infrared range. This spectral pattern makes it possible to identify the sweet potato crop with a high degree of certainty, which allows defining with precision the cultivated area and the spatial distribution of the crop through the utilization of high-resolution SPOT images. The results suggest that the traditional statistics underestimate the total annual sweet potato cropping area in Kumi. The use of the tested method substantially improves the estimation of cropping areas.

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Comparative assessment of soil carbon stocks in different agroecologies in Southern Peru

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Abstract

Soil carbon sequestration in cropping systems, in spite of its importance, is seldom quantified in Peruvian soils. A study was conducted to analyze soil carbon sequestration in different ecosystems of Peru, as affected by soil type, altitude, climate, cropping system and management regimes. Soils were sampled from a transect of approximately 1000 km from sea level to 4000 masl and spanning the coast, the plateau and the eastern hillsides. Potato is usually the rotation head of most of these systems, except in the Amazonian sites. Samples from 0 to 30 cm depths were taken and processed for total carbon stocks (CS). Whole soil samples were also characterized using the Laser-Induced Fluorescence (LIF) Spectroscopy to assess the carbon stability in the different agroecologies. The soils in the Amazonian site presented higher CS -together with dry valleys- but with lower stability, when compared to other agroecologies. Higher soil carbon stability increased with depth, due to the presence of recalcitrant carbon, while at the surface the presence of labile carbon dominates due to constant input of plant residues. The data supports the hypothesis that diversified production systems with potato, alfalfa, oat, corn, beans, onion – depending on the altitude- and livestock are more stable from a system's whole productivity point of view, which includes CS and stability. Thus diversification strategies are needed to guarantee the conservation of ecosystems with high CS and might be essential to help farmers adapting to the effects of climate change, a challenge to be faced in the near future.

Keywords: Peruvian soils, soil carbon stocks, carbon stability.

Introduction

Carbon sequestration in plant and soil systems provides an opportunity for agriculture to contribute to the mitigation of the greenhouse effect. Although the Clean Development Mechanism (CDM) protocol has prioritized only aboveground carbon sequestration via reforestation and forestation, the soil, including some agricultural soil, might represent even a larger carbon sink. One of the challenges for the incorporation of agriculture into post-Kyoto agreements is to develop simple and effective methodologies for measuring, monitoring and verifying soil carbon in cropping soils. For this end, field-level measurements that guarantee reliable assessments of soil carbon contents and quality are needed. EMBRAPA has been very active in the development of portable equipment to suit these needs. The best examples are the laser induced breakdown (LIB) spectroscopy to quantify- amongst other elements- carbon contents in the soil (Ferreira et al., 2008; Da Silva et al., 2008) and the laser induced fluorescence (LIF) spectroscopy, which relies on the fluorescence emitted by rigid conjugated systems and thus can be used to assess the degree of humification in the organic matter of whole untreated soil samples (Milori et al. 2006).

The LIF signals emitted by whole soil samples after excitation with ultraviolet radiation (351 nm) are unambiguously due to the organic matter fraction and the results agree with other spectroscopic methods such as Electron Paramagnetic Resonance (EPR) (Saab & Martin-Neto 2004; Saab & Martin-Neto, 2008), Nuclear Magnetic Resonance (NMR) (Leifeld & Kögel-Knabner, 2005; Saab & Martin-Neto, 2007,) and Fluorescence spectroscopy (Milori et al., 2002; González-Pérez et al., 2007). According to Milori et al. (2002), fluorescence signals with excitation at near ultraviolet or blue radiation are more resonant with rigid conjugated systems in individual molecules or structures (probably aromatic) bearing constituents such as carbonyl and carboxyl groups.

The International Potato Center (CIP) and two Brazilian institutions –the Brazilian Agricultural Research Corporation (EMBRAPA) and the University of Sao Paulo (USP) - have joined forces and resources to: a) assess soil carbon sequestration in different agricultural soils in the Peruvian Andes; and, b) estimate the degree of chemical recalcitrance of the soil organic matter – organic matter resistance to biodegradation- using state of the art non-destructive analytical methods that determine not only the recalcitrance index but also a more detailed chemical composition present in the humic substances or the soil structure.

Methods

Sampling transect

Southern Peru has such contrasting agroecologies that might mimic the extreme conditions found in tropical agriculture throughout the world. Coastal, Amazon and high mountain regions are part of the landscape. The changing altitude and orography of the mountain chain produces a diversity of temperature, rainfall and humidity patterns, which have direct effect on soil development. Tropical rainforests are found at the windward eastern hillside while the leeward western hillside is a desert. Based on geology, soil, altitude, climate, and land use data, an approximate 1,000 km sampling transect was selected (Figure 1). The transect included five major agroecologies: arid coast, arid low altitude inter-Andean valley, arid high altitude inter-Andean valley, semi-arid high plateau, and the tropical rainforest. Soils from the main cropping systems within each agroecology were sampled. Irrigated agriculture on the western hillside, of about 500 years, is the most recent one. Most important crops in this agroecology include: maize, olive, alfalfa, potato, grape, and avocado. Further up, the high plateau is the center of origin of potatoes and one of the most important millenarian crop domestication centers in the world. Soils from rotational cropping systems, the predominant practice in the area, were sampled in this agroecology. On the Amazonian side, soils from a primary rainforest and cultivated shaded coffee were included.

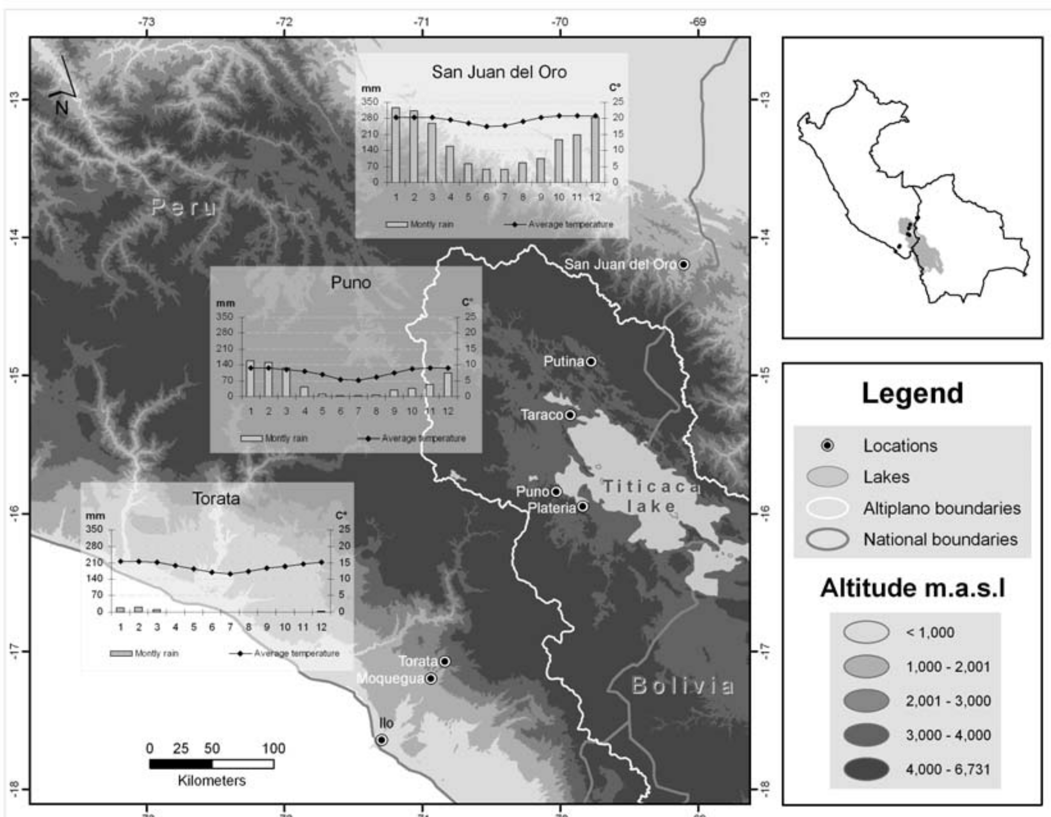

Figure 1. Sampling-transect to assess carbon contents and stocks in Southern Peru

Experimental

In each sampling site, five layer samples from 0 to 30 cm depths were taken and processed for total carbon analysis (Table 1), which was performed on approximately 200 mg aliquots of soil samples using a total carbon analyzer (LECO model CR 412). Carbon contents (CC, in g kg^{-1}) and Carbon stocks (CS, Mg ha^{-1}) were estimated in each layer and throughout the entire profile. Humification degree of organic matter present in whole soil samples was estimated using LIF spectroscopy through the estimation of the H_{LIF}, a ratio of the area under the fluorescence emission (excitation range 350 - 480 nm) and the total organic carbon content in the sample. Soil pellets of approximately 0.5 g, 1 cm of diameter, and 2 mm thickness, were inserted into a home-assembled apparatus to acquire LIF data (Milori et al., 2006). Samples were excited with 458 nm blue radiation, emitted by argon laser equipment (Coherent Innova 90-6, Coherent Inc., Santa Clara, CA) with power of around 300 mW. The system apparatus was assembled according to Milori et al. (2006). Using a nested sampling scheme, CC and CS were compared, among cropping systems within agroecologies and among agroecologies.

Results and discussion

As shown in table 1, both the shaded Amazonian coffee and alfalfa in the high altitude inter-Andean valley presented the largest CS in the soil (91 Mg ha^{-1}). These cultivated areas had larger CS than the tropical rainforests soils (75.2 Mg ha^{-1}). The olive orchards in the arid coast had the lowest CS (38 Mg ha^{-1}). Carbon stocks in potato and maize systems varied from 42 to 56 Mg ha^{-1}, depending on the location. Our results also showed that soil organic carbon increased with elevation in the arid environments, as evidenced by the fact that when CS was analyzed as a function of altitude for different agroecologies, within the same texture class, a linear relationship ($r \sim 0.8$) was obtained, which confirms some observations found in the literature.

The degradability of the readily bioavailable dissolved or water-extractable OM fraction is often negatively correlated with its aromatic compounds content, which in turn has been associated with recalcitrance (soil carbon stability). The results are given in arbitrary units (a.u), typical of indexes, and are calculated by dividing the area of the LIF spectra (a.u.) by the corresponding carbon concentration (g kg^{-1}). The soils in the Amazon site presented lower carbon stability. Soil carbon stability increased with depth, due to the presence of recalcitrant carbon, while at the surface the presence of labile carbon dominates due to constant input of plant residues.

Organic matter in soils under irrigation and subjected to conventional tillage in the arid ecosystems is more recalcitrant (I don't observe this in B3, B3 is similar than A4 and B4, they are more labile) than in soils with less tillage or where tillage is done manually like in the plateau. In the literature this is usually related to the decomposition of labile organic matter caused by tillage. It was also noteworthy the uniformity in the humification degree across layers in soils under conventional tillage, which is usually associated with the homogeneity imparted by tillage disturbances of the top layers of these soils. Less- or no-tilled soils showed a gradient, attributed to the higher input of recent organic matter by crop residues and plants to the top layer. These findings confirmed trends found in previous research by the team.

Table 1. Carbon stocks (Mg ha^{-1}) by soil layer and total carbon storage per soil site. Data from soil sampled in 2008, in different cropping systems

Depth (cm)	Carbon Stocks (Mg ha^{-1})#									
	Ilo		Moquegua			Torata		San Juan del'Oro		Puno
	A1	B1	A2	B2	C2	A3	B3	A4	B4	A5
0-2.5	4.4	3.6	5.9	4.7	6.5	7.4	11.9	10.6	8.3	3.7
2.5-5	4.0	3.4	4.9	4.7	6.4	7.6	10.8	9.2	7.0	3.8
5-10	6.8	6.5	7.2	9.0	11.3	14.8	15.9	15.3	11.1	9.8
10-20	13.4	12.8	19.5	18.0	23.3	22.4	28.3	32.2	26.5	17.2
20-30	13.8	11.8	19.2	19.2	17.7	16.0	25.0	24.0	22.3	12.4
Total	**42.4**	**38.1**	**56.7**	**55.6**	**65.2**	**68.2**	**91.9**	**91.3**	**75.2**	**46.9**

Carbon stocks = $10 \times (C \times d \times T)$; C is the carbon content in g kg^{-1}; T the sample layer thickness in meters and d the soil layer bulk density in Mg m^{-3};
A1: maize; B1: olive; A2: alfalfa; B2: potato; C2: grape; A3: avocado (intercropping); B3: alfalfa under irrigation; A4: coffee; B4: original forest; A5: alfalfa – potato – oat rotation

Table 2. Humification degree (H_{LIF}) of soil in different Peruvian sites, obtained through Laser Induced Fluorescence (LIF) spectroscopy at 0-2.5, 2.5-5, 5-10, 10-20 and 20-30 depths

			Depth (cm)				
	site	**crop**	**0-2.5**	**2.5-5**	**5-10**	**10-20**	**20-30**
H_{LIF} (a.u.)	Ilo	A1	21.5±1.4	24.4±0.1	24.6±1.3	23.8±1.2	24.6±1.8
		B1	27.6±0.2	28.3±0	28.4±0.0	29.0±0.3	32.0±0.3
	Moquegua	A2	18.9±0.1	22.6±0.1	21.1±0.1	23.3±0.2	22.4±0.8
		B2	23.5±0.2	23.8±0.0	24.5±0.1	24.1±0.1	22.5±0.1
		C2	19.4±0.1	19.5±0.1	21.4±0.0	23.6±0.0	30.2±0.1
	Torata	A3	18.6±0.2	19.9±0.2	19.2±0.5	29.7±0.3	37.4±0.2
		B3	10.5±0.0	11.5±0.1	15.9±0.2	18.6±0.1	19.2±0.1
	San J. Oro	A4	7.6±01	8.8±0.0	10.6±0.1	12.1±0.2	18.1±0.1
		B4	8.7±0.2	10.2±0.0	11.3±0.1	13.38±0	19.3±0.1
	Puno	A5	16.5±0.1	16.8±0.2	17.7±0.08	21.0±0.8	24.6±0.1

A1: maize; B1: olive; A2: alfafa; B2: potato; C2: grape; A3: avocado (intercropping); B3: alfafa under irrigation; A4: coffee; B4: original forest; A5: alfafa – potato – avena rotation

The study also included a successful preliminary evaluation of portable optical techniques for future agriculture applications in soil characterization. The portable LIF (optical sensor) might evaluate the soil organic matter in the field, connected to a GPS for producing soil quality maps. A portable LIBS (Laser Induced Breakdown Spectroscopy) system is also promissory equipment. LIB spectroscopy can carry out quantitative field analysis of carbon contents and other elements in the soil. With these new tools, soil carbon sequestration studies as well as macro and micro soil nutrients assessment for soil amendments and contaminants in the soil can be implemented in the field without (or minimal) sample preparation.

Conclusions

Soil carbon stocks varied across cropping systems in different Andean agroecologies. Well managed agricultural soils can result in positive carbon balances and contribute to clean (carbon dioxide wise) food production. As a matter of fact, carbon stocks in some of the cropped area were similar to those obtained in primary rainforests. Nonetheless, the degree of humification is higher in cropping systems than in primary forests indicating that carbon stocks in cropping systems tend to be more recalcitrant. However, the lack of metabolizable organic compounds must also be taken into account. The non incorporation of fresh available residues containing compounds necessary for the metabolism of microorganisms leads them to decompose the organic matter already existing in the soil more thoroughly. (Because this, a crop system with more recalcitrant carbon can't be good for carbon sequestration)

The study also demonstrated the potential of using spectroscopic systems of highly reliable results for field-level analysis of carbon contents and their degree of humification. The H_{LIF} ratio can be used to discriminate, in whole soils, the variation in degree of humification at depth for different crops and tillages, showing the effect of constant accumulation of plant residues in the topsoil.

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Minimum tillage systems with winter-potato in Southern China

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Abstract

With the introduction of early maturing rice varieties in subtropical China, the later planting of the spring rice and the earlier planting and harvesting of summer rice resulted in a fallow period of 90–120 days during winter to spring. The mild cool temperatures of this season are suitable for vegetable or potato production, which opens the opportunity to increase food production and farmers' income without competing for arable land or clearing forests.

Heavily worked rice soils often have high clay content and are low in organic matter, and therefore difficult to plow. In China, some farmers have tackled this problem through minimum tillage and mulching. They basically place potato seeds on the ground and cover them with a thick mulch of rice straw. The crop then develops with irrigation or in rainfed conditions, producing yields of 15 to 30t/ha. A product of farmer innovation, the system has not been long in use.

Usually farmers use the straw from two to three hectares of rice to mulch a single hectare of potato. The rice straw is an important source of organic material that also benefits the subsequent rice crop. However, alternative uses of the straw (feed, fuel) might limit the application of this cropping system.

Since 2008 the International Potato Center is analyzing the potentials and constraints of this system via researcher and farmers surveys and the implementation of on-farm trials to improve management components and productivity. The system might have the potential to serve farmers in regions with similar agro-ecological conditions.

Keywords: rice straw, fertilizer management, mulch.

Introduction

In 1993 China became the world's leading producer of potatoes (Wang and Zhang, 1993). Since 1990, there has been a steady increase in cultivated area and total production (FAO, 2007) and it is expected that the proportion of arable land for potato cultivation will further grow (Janski et al, 2009). Reasons are an increased demand of potato from the processing industry, a growing population and the high profitability of the potato crop compared with other food crops in China. Although potato ranks fourth in importance following rice, maize and wheat, a large percentage of maize is used for animal feed while most of the potato yield is designated directly for human consumption.

In the future a further expansion of the area devoted to potato production will either be on the expense of other crops or pushing potato cultivation into the drier regions which actually account for 60% of China's arable land but probably have a low inherent productivity because of droughts and other biotic and abiotic constraints. A third option would be to gain arable land by an intensification of land use systems, making use of fallow periods between crops, introducing an additional crop, in this case potato, in an existing system without affecting its former productivity. The advantages would be that 1) no new land had to be developed, 2) experienced farmers would manage the new crop/cropping system, 3) the additional crop would generate an extra income, and 4) a more diversified cropping system could have beneficial effects on productivity and/or plant health, i.e. crop quality.

Such an opportunity, to increase food production without competing for arable land, arose with the introduction of early maturing rice varieties in the cropping systems of subtropical China. The earlier harvesting of the summer rice crop and the later planting of the spring rice crop resulted in a fallow period of about 120 days of paddy rice soils in winter time. The mild cool temperatures of the season are suitable for vegetables and potato or sweet potato production. However, heavily worked rice soils often have high clay content and are low in organic matter, and are therefore difficult to plow. Preparing a fine textured seed bed as normally done for commercial potato production would be too time consuming and laborious. In the Southern provinces of China, some farmers have tackled this problem through minimum tillage and mulching. They basically place potato seeds on the ground and cover them with a thick layer of rice straw. The crop then develops with irrigation or in rainfed conditions, producing yields of 15 to 30 t/ha.

Usually farmers use the straw from two to three hectares of rice to mulch a single hectare of potato. The rice straw is an important source of organic material that also benefits the subsequent rice crop. However, alternative uses of the straw (feed, fuel) might limit the application of this cropping system.

As product of farmer innovation, the system has not been long in use, and neither has it been investigated thoroughly. Since 2008 the International Potato Center is analyzing the potentials and constraints of this system via researcher and farmers surveys and the implementation of on-farm trials to improve management components and productivity. A second objective of this study would be to evaluate the suitability of this system to serve farmers in regions with similar agro-ecological conditions in South or Southeast Asia making use of several million hectares of developed farm land for potato production.

In this paper we will present the results of a researcher and farmer survey conducted in 2008 and 2009 in order to give more insights in the driving factors, the constraints and opportunities of the winter-potato-mulch system. Based on these results on-station and on-farm trials will be developed and implemented during two growth seasons 2009/10 and 2010/11.

Materials and methods

The researcher survey was developed in 2008 and sent to research staff and extension officers of the nine provinces where the potato-mulch system is either in use to some extent or which have the (climatic) potential for the system to be introduced and diffused and therefore researcher are testing it in field trials. The provinces belong to three of the four major agroecological zones of China (Jansky et al, 2009), the Central double cropping zone (Anhui), the South winter cropping zone (Fujian, Guangdong, Gungxi) and the Southwest mixed-cropping zone (Chongqing, Guizhou, Hunan, Sichuan, Yunan). The questionnaire had about 15 mostly open questions. The objective of this survey was to get information about past or current research activities related to the potato-mulch system, a brief assessment of its major constraints and opportunities and a description of its implementation and management by farmers in the different provinces. Additionally to the survey, the researcher met for a two day workshop in Changsha, Hunan, to present information and to discuss further research activities on project and national level. Additionally field visits were organized for CIP researchers in Hunan, Chongqing and Guangxi provinces.

Based on the research survey and field visits a questionnaire for farmers was developed with 47 open and closed questions regarding crop management in general and the experience with the potato-mulch system specifically. In 2009 a total of 78 farmers were interviewed in the provinces of Fujian, Gungxi, Chongqing, and Hunan. In each province farmers from 1 to 3 villages per county and 1 to 5 counties per province were surveyed, with a total of 24 farmers per province, except for Hunan with 6 farmers only, because the potato-mulch system was not widely used in this province. In Fujian province few farmers had rented comparatively large areas of land, ranging between 6 and 80 ha. These areas were not considered if average land areas or areas under specific crops were calculated.

Data were analyzed using descriptive methods, correlations and linear regression models for results obtained from questionnaires.

Results and discussion

Potato-mulch system

Field visits showed that farmers used several types of minimum tillage potato-mulch systems (Photos 1). They either planted potato in double rows on ridges about 0.90 m wide covering them with a thick layer of straw, which then was covered with soil for better protection against low temperatures or prepared seed beds about 1.60 m wide for 4 rows of potato. The seed beds were sometimes slightly raised but often the seed tubers were placed directly among the rice stubble. Then the seed was covered with a thick layer of straw. Farmers principally used rice straw as mulch material and depending on the specific potato-mulch system and climatic conditions the straw of 1 to 3 ha of rice was required to mulch 1 ha of potato. Depending on the temperatures during sprouting and emergence the straw cover (of ridge or bed systems) could be further covered with plastic foil. The plastic serves the dual purpose of protecting against low temperatures and excessive moisture in regions with winter rains (Hunan).

In these systems potatoes were planted in high densities of 70,000 to 90,000 plants/ha. Depending on the region they were either irrigated or left to grow in rainfed conditions. For harvest the straw or straw soil cover was removed to collect the potato tubers, which resulted in a great reduction of labor compared with conventional systems. Farmers planted several potato varieties; either improved Chinese varieties or imported Dutch or German ones with a growth period of about 100 to 120 days. Reported yields averages ranged between 12 and 25 to 30 t/ha depending on the climatic conditions of the region and management skills of the farmers.

Photos 1: 1-seed bed with 4 rows of potato; 2-ridges with double rows; 3-straw mulch + plastic foil; 4-potato tuber under straw mulch; 5-tuber production in straw mulch; 6-harvest

Research information

First investigations of the potato-mulch system started in some regions about 8 years ago; meanwhile research programs have been implemented in all nine provinces. According to the researchers the winter potato crop has to compete with crops such as rape, winter wheat, vegetables, fruits or maize. The advantages of the potato-mulch system were described as generating relatively high yields, while production costs are reduced because the system is less labor-intensive, requires less pesticide inputs and conserves the soil against erosion and nutrient leaching. The potatoes are generally of good quality fetching a high price in the market. The increased land use intensity, by adding a commercial crop, gives the farmers an extra income. The main constraints are seen in the poor quality of seed resulting in lower yields, in the great straw quantities needed, in a high percentage of green tubers if potatoes are not thoroughly covered, in a slow and non-uniform emergence caused by low temperatures and a lack of early maturing varieties. As possible alternatives for rice straw the researchers mentioned straw from wheat and maize, sugar cane leaves or plastic foil.

Nevertheless, the area planted to the potato mulch system increased steadily in recent years indicating that farmers value the system and that the economic advantages are apparently greater than the prevailing constraints (Table 1).

According to the scientists there are three major factors which could hamper the expansion of the system. These are the availability of sufficient rice straw, the capacity of the extension service to train farmers and the necessity of a clear economic benefit for the farmers.

Ongoing and past research has been directed towards the development of adapted crop management technologies such as planting densities, planting and harvesting times, the use of different straw quantities and testing of distinct cover materials, the screening of varieties for earliness, drought and frost tolerance as well as late blight and fertilizer management. However, research efforts have been on a relatively small scale and need to be intensified to generate improvements and innovations to further increase productivity of the potato-mulch systems. Hence, research needs for further scientific investigations were identified as 1) the development and screening of adequate varieties (earliness, drought tolerant and adapted to low temperatures), 2) improvement of the fertilizer use efficiency and 3) the development of (integrated) crop management technologies to improve yields.The national research community has recognized the value of the winter-mulch system in generating more food and economic benefits without investing considerable resources or cultivating new land. Past and ongoing research has identified and described constraints and opportunities of the system. Further research needs have been clearly articulated but would probably need a more coordinated (interdisciplinary and interprovincial) effort to generate outputs in the near future. However, the vast areas in China and neighboring countries, which have adequate climatic conditions and appropriate cropping systems to accommodate an additional winter cropping season might convince decision makers to provide the required resources for the further expansion of the potato-mulch system.

Table 1. Development of land area under potato-mulch cultivation in 9 provinces of China and potential land for further expansion

Province	Potato-mulch area in ha			Areas for potential expansion
	1997	2002	2007	
Guangdong	1,300	3,700	6,400	in double cropping areas of southern China with winter cropping regions - potential up 1.2 million ha
Sichuan	25,000	35,000	46,000	in surroundings of bigger cities
Chongqing	none	3,700	20,000	in medium elevation areas <800m asl only 15% of the 135,000 ha rice area are planted with fall potato
Gungxi	none	None	93,000	30,000 to 60,000 ha in rice and sugarcane fields; especially south of the tropic of cancer:
Guizhou	none	None	83,000	in southern regions with paddy rice fields
Anhui	None	None	14	in the rice planting area between Yangtze and Huaihe River
Yunan	no data			no estimates
Hunan	no data			about 2 million ha of potential farmland in the South which could be used for winter potato
Fujian	no data			some potential in less developed regions with abundant rice straw

Farmer information

Farmers interviewed had an age average of about 50 years with more than 30 years working on their farm. About 50% were part time farmers looking for additional income with jobs in cities or as traders. The average farm size was with 0.27 ha rather small, but 42% of the farmers rented more land for crop production, increasing the average cultivated land per farmer to 0.38 ha. Usually land is cropped thrice per year.

The spring crop is planted in March/April, the summer crop follows in July/August and in November/December the third season starts. However in Chongqing, because of low temperatures, farmer plant often only twice and leaving the fields fallow in winter (Figure 1). Rice was mentioned by 96% of all farmers as the most important subsistence crop, while for 79% of the farmers potato was of specific commercial importance.

Potato was grown on 0.10 to 0.15 ha of land on average, except for Fujian province where the potato area was larger with about 0.33 ha (about 25% of the farmers in Fujian rented large areas increasing the mean potato area for that province to 6.8 ha). In Fujian farmers stated that they were growing potatoes with straw mulch for about 9 years, while in the other provinces farmers had only 2 to 3 years of experience with the system. The average yields achieved ranged between 11-14 t/ha for Chongqing and Hunan up to 25-30 t/ha in Fujian and Gungxi. Most farmers used their own rice straw for potato planting or could obtain it for none or little costs, however, transport seemed to be a more crucial cost factor. 25% of all farmers used some insecticides and about 50% fungicides to control late blight. Labor input amounted to about 21 man-days for field preparation, and 30 man-days each for planting and harvesting. The major cost factor was probably potato seed, as there are no seed storage facilities in the South and farmers have to renew their seed annually. About a third of the farmers was not content with seed quality and complained about low emergence, different varieties mixed together, virus infections and rotten tubers. Another crucial input was inorganic fertilizer, which farmers apply in high quantities to rice and potato. A significant difference in fertilizer management between the two crops is that potato receives often a more balanced N-P-K application and organic manure while rice is cultivated with a nitrogen based fertilization and little manure applications (Figure 2). A crude balance of applied and removed nutrients shows that fertilizer is not used efficiently and might therefore cause environmental damage but at least constitutes a cost factor, which reduces farmers' income.

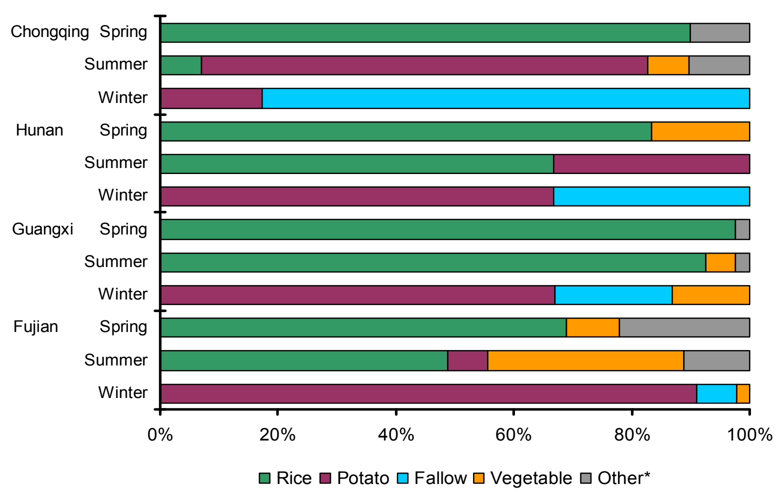

Figure 1. Frequency of crops in farmers fields during an entire cropping cycle in 4 provinces of China, 2008/09. (*other crops are peanuts, sweetpotato, green soybean, maize)

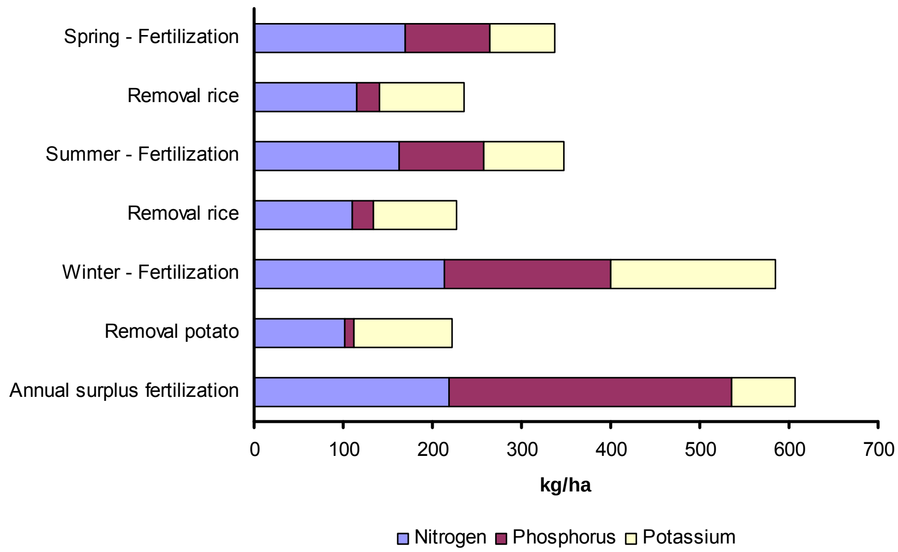

Figure 2. Nutrient applications and nutrient removal by crops during one year

Although farmers appreciate the extra income and the reduced effort in labor, they are also aware about further improvements of their present cropping systems. They specifically stress the importance of a better fertilizer management, the more efficient use of straw, to reduce transport costs and enable the cultivation of larger areas, the improvement of management techniques (planting dates and densities, furrow depth, mechanization etc.) and the provision of a higher seed quality.

Conclusions

The potato-mulch system allows farmers to crop their land up to three times a year. It provides the households with an extra crop and a substantial extra income. The potatoes are cultivated on medium to heavy, formerly inundated, rice soils, which have the advantage of a relatively constant water supply by residual soil moisture and quasi eliminates soil borne diseases or insects. Labor requirements are limited due to the minimum tillage approach and the fact that tubers can be harvested almost from the soil surface.

Hence the system requires few resources for pesticides and labor but needs great amounts of rice straw, seed tubers (provided from the Northern provinces) and fertilizer. Other constraints are often of abiotic nature such as low temperatures in some provinces retarding emergence and affecting plant growth or too little or too abundant rainfall, requiring extra drainage or irrigation.

The system was developed by farmers and operates with a sound profitability; however, raising costs for agro-chemicals, seed and labor affect these margins and require an improvement in productivity and resource use efficiency. That is why farmers claim support in the development of adequate fertilizer management and more efficient cropping management technologies such as plant densities, planting dates, straw application etc. Furthermore, the selection or breeding of early-maturing varieties, adapted to low temperatures would facilitate the expansion of the system to the more temperate zones.

In a second phase the project in collaboration with Chinese NARS will test crop management options in on-station and participatory on-farm trials with the objective to increase yields and improve input-use-efficiency and evaluate the options of expanding the technology to other potential winter cropping zones.

Acknowledgements

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Estimating daily rainfall from NDVI using the wavelet transform

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Quantifying rainfall at spatial and temporal scales is a challenge posed to scientists in different disciplines given its importance in agriculture, natural resource management and land-atmosphere interactions. This paper describes a new approach to assess rainfall combining rain gauge data with the normalized difference vegetation index (NDVI) based on the fact that both events are periodic and proportional. The procedure developed to reconstruct the rainfall signal combining the Fourier Transform (FT) and the Wavelet Transform (WT) is described. FT was used to estimate the lag time between rainfall and the vegetation response. Third level decompositions of both signals with WT were used for the reconstruction process, determined by the entropy difference between levels and R^2. The low frequency signal from the NDVI data was used as the base signal for the reconstruction to which the high frequency signal (noise) extracted from the rainfall data was added. The reconstructed daily rainfall was compared to the measured one obtaining determination coefficients > 0.81. This finding is quite an improvement over the estimates reported in the literature where this level of precision is only found for comparisons at the seasonal levels. This methodology has clear scope to improve spatial interpolation of rainfall based on high-resolution NDVI fields and a limited number of meteorological stations.

Keywords: Rainfall, NDVI, transforms, wavelets, Fourier, and reconstruction.

Introduction

Numerous studies have used the intuitive correlation between rainfall and biomass, particularly in arid and semi-arid environments to fill in this rainfall data gap (see Richard and Poccard, 1998; Kawabata *et al*., 2001; Nicholson and Farrar, 1994; Farrar *et al*., 1994; Nicholson *et al.,* 1990; Eklundh, 1998; Martiny *et al.,* 2006; and Dinku *et al,.* 2008). The vegetation response to precipitation is highly variable in space, mainly due to soil and other factors influencing the vegetation response. The delayed response in time (lag) has been termed residence time (Farrar *et al.,* 1994) and defined as the time required for a volume of water equal to the annual mean of exchangeable soil moisture to be depleted by runoff and evapotranspiration. This lag time varies for different agroecologies; in semiarid regions it is usually on the order of 2-3 months (Nicholson and Lare, 1990). A linear relationship between rainfall and NDVI has been reported for areas with precipitation ranging from 200 to 1200 mm per year (Nicholson *et al.,* 1994). Above the upper threshold, the index "saturates", and NDVI increases only very slowly with increasing rainfall or becomes constant. Actual procedures for estimating rainfall from NDVI are of limited use in applications in modeling agricultural production, and land-atmosphere interactions studies, where dekadal or daily rainfall is required. The present study aims to develop a methodology to reconstruct daily precipitation based on NDVI and precipitation data, to further improve spatial precipitation fields with a high temporal resolution through a robust procedure. Secondly the focus is on the assessment of the lag time and a further analysis of vegetation response to rainfall.

Materials and methods

Study area

The Altiplano is a high Andean plateau centered geographically and socioeconomically on Lake Titicaca. The plateau rises from the lake level at 3,800 meters (m) to over 4,500 m altitude and is bisected by the international border between Peru and Bolivia. For more details see Quiroz *et al*., 2003. The analysis presented in this paper addresses the rainfall situation on the Peruvian side.

Climate data

Rain-gauge daily data from 10 weather stations were obtained from the Peruvian national meteorology and hydrology service (SENAMHI). The period January 1st 1999 through December 31st 2002 was used in the analysis.

The raw data was checked for consistency and outliers. The analysis was conducted for the ten sites where the weather stations were located.

NDVI data

A dataset containing 197 10-day (dekad) composite NDVI images derived from the SPOT-4 and SPOT-5 VEGETATION instruments was used, spanning the period January 1999 through December 2003. Both sensors have the same spectral and spatial resolution. The red spectral band (0.61–0.68 mm) and the near-infrared (NIR) spectral band (0.78–0.89 mm) were used to calculate the NDVI (NIR-RED/ NIR+RED) and the imagery had a spatial resolution of 1 km. The GPS coordinates of the weather stations were co-registered with the NDVI imagery for the extraction of the data corresponding to each site. The dekadal NDVI value was repeated for each day within the respective dekad to match the daily observations in the rainfall data. These original NDVI values were multiplied by the ratio of the mean value of both signals to generate magnitudes comparable to those registered for rainfall.

Data pre-processing

Fourier analysis

For a rainfall process described by a function S(t), the Fourier series can be expressed as (Pipes and Harvill, 1971):

$$S(t) = \frac{A_0}{2} + \sum_{n=1}^{n=\infty} C_n \cos(nwt - \theta_n) \qquad (1)$$

The constant term in equation (1) is always equal to the mean value of the equation, e.g. the mean NDVI value in a series of satellite imagery. The signal is decomposed in a series of cosine terms, each with its own amplitude (C_n) and phase angle (θ_n), and a constant term ($A_0/2$) and $\omega = 2\pi f_0$, where f_0 is de base frequency. When a signal is described using Fourier analysis the values for the coefficients C_n need to be found.

Determination of the time lag

The time lag between the onset of the rainy season and the greening of the vegetation was assessed with the Fourier analysis. Both rainfall (S_{Rain}) and NDVI (S_{NDVI}) signals were reconstructed with the six first harmonic components (n=0 to 6 in equation 2) of the Fourier series, with sizes N and M, respectively. By including six harmonics in the simulation of rainfall and NDVI signals, most of the variance in the original data is explained (Immerzeel *et al.,* 2005). These smoothed Fourier transform (SFT) signals were used to estimate the lag between the two (Yarlequé *et al.*, 2007; Yarlequé, 2009). A new independent variable was generated through the simulation of the SFT for different periods T (where $T \in Z^+$). Out of all possible periods, T= 15, 30, 91, 121, 182, and 365 d were used for the analysis. Partitions $P_T = \{0, T, 2T, \ldots, kT\}$, $k \varepsilon Z^+$, with respect to T and $kT < N,M$, were defined. Each partition divided both signals (S_{Rain} and S_{NDVI}) into several sub-intervals. These intervals were used to search for the lags. Then the average lag over the k-sub-intervals was obtained as:

$$Lag(T) = \langle lag_k \rangle = \langle \Delta t_k \rangle, \qquad (2)$$

where the <> symbolizes average over *k*. Thus, we are estimating the lag as a new function *Lag(T)* (equation 2), of the period *T*. The best coefficient of determination was used for determining the residence time for each meteorological station.

Wavelet analysis

The wavelet transform is localized both in time and frequency and it has compact support. This property of wavelets is called time-frequency localization (Foufoula–Georgiou and Kumar, 1994).

The Wavelet Transform (WT)

The Wavelet Transform (WT) is defined as (Foufoula–Georgiou and Kumar, 1994):

$$WTS(\lambda,\tau)=\int_{-\infty}^{\infty}S(t)\psi_{\lambda,\tau}(t)dt, \qquad (3)$$

Where,

$$\psi_{\lambda,\tau}(t)=\frac{1}{\sqrt{\lambda}}\psi\left(\frac{t-\tau}{\lambda}\right), \qquad (4)$$

Here λ>0 represents the scaling factor (the wavelet's width) and τ the shifting factor (the wavelet's position). The mother wavelet function (*ψ(t)*) is generally chosen to be well localized in space (or time) and frequency (or scale). Not every function can qualify to be a mother wavelet (Mallat, 1999); it must meet the admissibility condition, described by Foufoula-Georgiou and Kumar, 1994. The Inverse Wavelet Transform (IWT) is deduced from equation (3), i.e. the S(t) function can be reconstructed from the WTS (Prasad and Iyengar, 1997). The Multi-Resolution Analysis with Wavelet (MRA) is described in more details in the works of Mallat, 1999; Daubechies, 1990; Foufoula–Georgiou and Kumar, 1994. This technique is used to implement a decomposition (upscaling) and a reconstruction (downscaling) of the S(t) function (signal) in several scales (levels), realizing a cascade process (Yarlequé *et al.*, 2007; Yarlequé, 2009; Foufoula-Georgiou and Kumar, 1994; Mallat, 1999). This cascade process is illustrated in the decomposition and reconstruction process with MRA in the results section.

Validation methods

The expected value of such a gain in information is defined as the entropy (H) of the system:

$$H=-\sum_{i=1}^{N}p_i \ln p_i \qquad (5)$$

Where p_i is the probability that the system assumes its i[th] possible outcome. Entropy concepts were also used for helping decide at which decomposition level to stop and to assess at which level the reconstruction should start. Entropy differences between the bases, ΔH = H(NDVI $Base_i$)- H(RAIN $Base_i$), such that $\Delta H \rightarrow 0$ was the criteria used. That is, when the internal information of the NDVI base is similar to the rainfall base. The R^2, the relative mean absolute error (MAE) and Bias (Dinku *et al.,* 2008), were use to validate the reconstruction results.

Results and discussion

Figure 1 shows an example of NDVI (panel a) and rainfall signal decomposition duly de-lagged. On the left hand column the low-frequency pass signals (low-pass), generated by the scaling function of the Symlet2 wavelet (Graps, 1995) are shown. They are labeled as RAIN $Base_i$ and NDVI $Base_i$ for rainfall and NDVI, respectively, for each decomposition level i=1, 2, 3. These signals correspond to the trend at each level of decomposition or resolution. On the right hand column, the high-frequency pass signals (high-pass) for both series (RAIN $Noise_i$ and NDVI $Noise_i$) are also shown. These signals provide information on the noise or variance contribution at each resolution i.

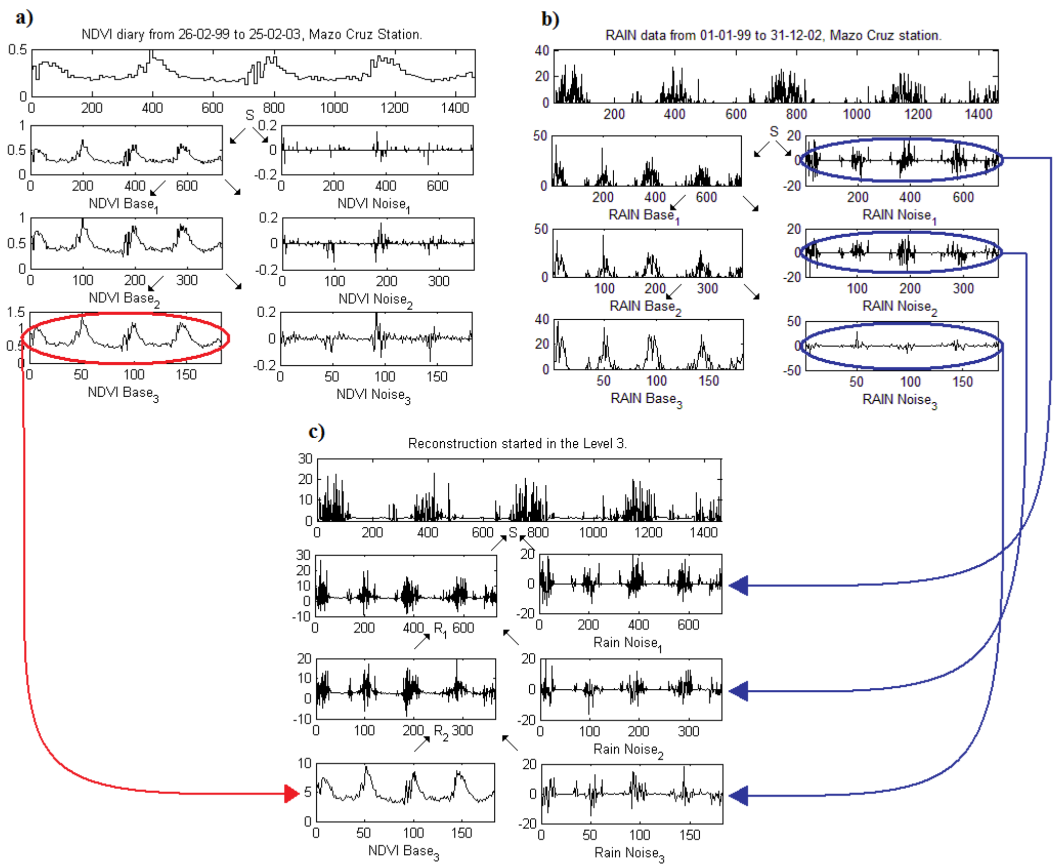

Figure 1. Signal decomposition at 3 levels, using the MRA technique for (a) NDVI (b) Rainfall data, following the arrows sense. c) Rainfall reconstruction process initiated at level 3, using the data shown in figures 1a and 1b, in the inverse arrows sense.

Table 1 presents different metrics for relating the degree of association between the bases of NDVI and rainfall signals at different levels of wavelet decomposition. The rightmost column contains the coefficient of determination. Based on this metric, a decomposition level 4 or 5 is needed to attain an acceptable R^2. Entropy and entropy differences were also used to determine the most suitable decomposition level. There was a steep decline in ΔH until the third level of decomposition. The entropy difference from this level onwards seems to level off (Table 1)

Table 1. Entropy, entropy difference, and R^2 values for the NDVI and rainfall bases for different decomposition levels

Level (*i*)	Scale ( )	H NDVI Base $_i$	H RAIN Base$_i$	H	[H/max(H)]*100%	R^2 from Base NDVI$_i$ vs Base RAIN$_i$
0	1day	149.41	273.82	124.4	100	0.18
1	2days	46.37	129.67	83.30	66.95	0.26
2	4days	8.36	50.67	42.30	34.00	0.36
3	8days	5.22	16.12	10.90	8.76	0.45
4	16days	4.54	5.55	1.01	0.81	0.58
5	32days	3.87	3.97	0.10	0.08	0.64

Rainfall reconstruction

An inverse wavelet transform can accurately reconstruct the original signal since all the information is contained in the base and noise vectors at each decomposition level (Figure 1c). Based on entropy (Table 1) and R^2, metrics used to assess the decomposition levels, the reconstruction started from the third level upwards.

Figure 1 graphically portrays an example of how the reconstruction looks like - using the inverse wavelet transform function (IWT, section 2.5.1 and the Symmlet 2 wavelet) - when the process is initiated at level 3. The low-pass signal from the third decomposition level of the NDVI (NDVI Base$_3$, in figure 1a), is combined with the high-pass signal from the same level of the rainfall (RAIN Noise$_3$, in figure 1b). This combination produces the signal labeled R_2. A second level reconstruction follows; for this step the reconstructed low-pass signal (R_2) is then combined with the high-pass signal from the rainfall (RAIN Noise$_2$, in figure 1b) to produce the R_1 signal. The same procedure is repeated in level one to produce the reconstructed rainfall signal (S).

Table 2. Changes in the determination coefficient as affected by the level where rainfall reconstruction starts: Mazo Cruz, with Lag(T)=53 and T=121

Level where the reconstruction started (*i*)	R^2: Reconstruction vs rainfall	R^2 (%)
1	0.56	-----
2	0.72	29.21
3	0.82	13.16
4	0.86	4.96

As explained above, the entropy analysis suggested that the level three was the minimum level recommended to obtain an acceptable reconstruction. The reconstructions were conducted from levels one through four. The increments in the proportion of the variance in measured daily rainfall explained by the reconstructed signal for each reconstruction were assessed (Table 2). The table shows both the determination coefficient and the additional explanation ($\Delta R^2=[(R^2_{(i+1)}-R^2_i)/R^2_i]*100\%$) produced when the decomposition level started at a higher level (i=1 through 4). As expected, R^2 increments as the level of reconstruction (i) moves from 1 to 4. It can be seen that when the reconstruction starts at level two R^2 increases in 29 %, compared to the reconstruction starting in level 1. This ΔR^2 substantially decreases when the reconstruction starts at levels 4 or higher (not shown). Levels 3 or 4 can be the starting points for reconstruction and the quality of the reconstruction is better than any estimation of daily rainfall from NDVI found in the literature (Figure 2). As a matter of fact, the robustness for estimating daily rainfall with this procedure is similar or better than monthly and seasonal estimations reported in the literature.

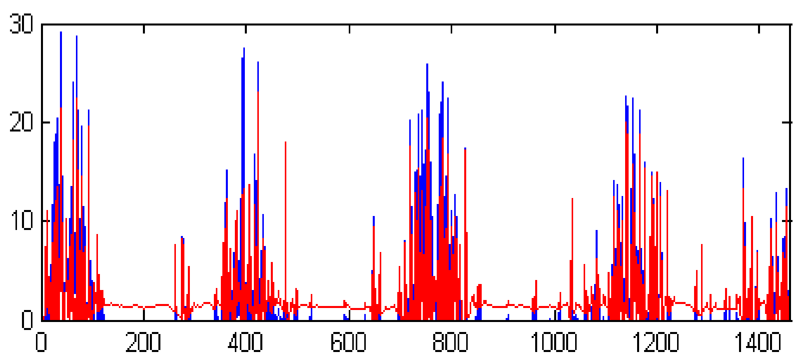

Figure 2. Rainfall reconstruction from NDVI trend and rain-gauge detail signal, using the inverse wavelet transform (blue=gauge; red=reconstructed)

Lag time

Table 3 shows the lag times estimated for S_{Rain} and S_{NDVI} time series using different periods T. It also presents the correlations between the measured rainfall time series and the reconstructed one using three decomposition levels. T=121 d was the best time resolution for analyzing the residence time across most ecozones. Only three of the ecozones showed better fit for other periods: Mañazo, Azángaro and Macusani (T= 365 d for the first two and 91 d for the latter).

Table 3. Determination coefficient for reconstructed versus gauged rainfall data and lag time for different sites in the high Andean plateau

Station	R^2	T (days)	Lag (T) (days)	MAE	Bias
Mazo Cruz	0.82	121	56	1.46	0.86
Mañazo	0.83	365	47	1.68	0.86
Huaraya Moho	0.85	121	86	0.9	0.84
Huancané	0.87	121	74	1.40	0.85
Azángaro	0.85	365	19	1.45	0.84
Macusani	0.91	91	84	1.01	0.87
Chuquibambilla	0.87	121	82	1.35	0.91
Desaguadero	0.82	121	57	2.12	0.84
Tahuaco Yunguyo	0.81	121	43	1.7	0.9
Ilave	0.81	121	76	1.93	0.9

MAE=relative mean absolute error.

Similar residence times were found in semi-arid regions in Africa with similar rainfall patterns (Farrar *et al.,* 1994; Nicholson and Lare, 1990; Brunsell and Young, 2008).

Conclusions

In this paper we showed a new reconstruction tool to generate daily rainfall from NDVI data, with the support of the Wavelet Transform, that maintain the same distributional properties of the measured events. The results obtained for the highly variable Andean highlands were superior to similar data reported in the literature. Actually the explanatory power of the reconstructed signal is comparable to exercises conducted at the seasonal level, using conventional statistical relationships between the two data sets.

Entropy analysis of the signals was a good metric to select the level of wavelet decomposition needed to maintain the distinguishing feature of rainfall events across space (point estimates within a region in this exercise) and time thus assuring a better representation of the phenomena being reconstructed.

The methodology described in this paper is suitable for interpolating daily rainfall from gauge measurement in specific points in space to larger areas. This can be accomplished by defining extrapolation domains for the stations and the support of NDVI measurements within the extrapolation boundaries, an investigation being conducted in our laboratory.

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Improving targeting of potato producing areas with process-based modeling

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Abstract

The International Potato Center (CIP) has targeted countries and regions (highlands, lowlands, temperate) where potato technologies could improve the livehoods of poor people, but in these huge geographical areas it is difficult to identify specific sites suitable for growing potato. An approach to identify and assess the areas with potential for potato production is described and applied to improve the targeting process. The potential potato areas were identified by the combined use of the Solanum simulation model and georeferenced databases. These databases included minimum temperature, maximum temperature and solar radiation. Monthly minimum and maximum temperatures were downloaded from www.worldclim.org; while solar radiation was estimated as a fraction of the extraterrestrial solar radiation for each geographical position. The model was run for 12 planting times (planting the first day of each month) for a standard potato cultivar. The sites and the cropping seasons with the highest yields were selected. Estimated potato yields were then complemented with livehood indicators for targeting CIP priority regions in Africa, Asia and Latin America.

Keywords: Simulation model, Geographic Information Systems, Targeting.

Introduction

CIP has conducted a global targeting exercise using indicators of livelihoods in areas where potato is an important crop (CIP, 2004, Theisen and Thiele, 2008). The target countries were divided into three regions, each with similar potato technology needs, which are: i) temperate zones – defined by geographical position, ii) Sub-tropical lowlands – a region that prioritized cereal-based systems where potato could be introduced to increase the system's productivity and iii) tropical and sub-tropical highlands – tropical and sub-tropical areas with altitudes above 800 meters above sea level (CIP, 2009). This type of exercise is limited by the quality of the reported production data of potato. In the present work, we tried to reduce the dependence on reported data and substitute them with data generated with process-based simulation models. This approach opens new possibilities since it is feasible to run alternative scenarios in the targeting exercise such as the inclusion of new genotypes with tolerance to heat or drought stress or the expected impact of climate variability and change.

Previous attempts to evaluate potato agro-ecology zoning for potato production have been done using potato simulation models (Van Keulen and Stol, 1995, Hijmans *et al*, 2003, Haverkort *et al*, 2004). Nevertheless the information generated is not available for use or analysis. In this work we used a Geographic Information System (GIS) linked to a potato simulation model to explore spatially the potential potato production using a standard cultivar and the effect of using a frost tolerant potato.

Methodology

Simulation model

Solanum is a slightly modified version of the LINTUL model (Stol *et al*, 1991), which was validated in the Bolivian highlands (Condori *et al.,* 2009). Solanum comprises a group of mathematical equations that uses daily weather variables (minimum, maximum temperature and solar radiation) and crop physiological parameters to simulate the development and growth of potato. Solanum is formed by three basic equations: thermal time, canopy cover and dry matter allocation. Thermal time or heat units are expressed in growing degree-days (GDD). There are many ways to calculate GDD (Raes *et al.,* 2009; Kropff *et al.*, 1994; MacMaster and Wilhelm, 1997); for our purposes the method proposed by Kropff was used. This method takes into account three cardinal temperatures: base temperature, optimum temperature and maximum temperature. For potato, these values are 2, 20, and 30°C, respectively. Canopy cover is used to calculate the intercepted photosynthetic active radiation (PAR) and transformed into dry matter through algorithms representing physiological processes.

Weather data

Monthly temperature and precipitation data - with a resolution of 10 arc-minutes (~18 km) were obtained from internet (Hijmans, *et al.*, 2005) and downscaled to daily intervals using a linear interpolation method. Solar radiation was estimated using the extraterrestrial radiation (Spitters *et al.*, 1986) and assuming an atmospheric transmissivity of 50 % and that the photosynthetic active radiation (PAR) is also 50 % of the radiation received by the plant.

Spatial version of Solanum

The potential production routine of the Solanum model (Condori *et al.*, 2009) and the methods to create weather input data (daily temperature and solar radiation) were programmed in a script language (Python) linked to a GIS program (ArcGIS). The final program named GeoSolanum was used to generate worldwide layers of potential potato production.

Growing season and cultivar

For each pixel 12 planting dates were run in order to obtain the potential productivity in each month. Simulation was initiated at emergence and run for a period of 140 days. The model was run with parameters of frost tolerant (*Solanum tuberosum ssp. andigena*) and non-tolerant germplasm (*Solanum tuberosum ssp. tuberosum*). The frost non-tolerant cultivar was used to identify regions with single and double growing seasons, and the difference between tolerant and non tolerant cultivars was used to estimate the possible impact of introducing frost resistant materials into the target countries identified by CIP (Theisen and Thiele, 2008).

Single versus double growing seasons

As explained above, 12 planting dates were tested for each pixel. To determine the primary cropping season, the planting month that produced the highest simulated yield was labeled. To eliminate sub-optimal yields of the same planting season, two months prior and after the labeled month were excluded from the search of the secondary season. The secondary season, wherever feasible, was selected from the remaining 7 months, based on the highest attainable yield in that period. Potential fresh tubers production exceeding 40 t ha^{-1} was the selection criterion. An additional water availability criterion, as described below, was also used. A map identifying single and double season target areas was produced

Masking non suitable potato areas

The potential potato production map was streamlined through the removal of the areas where potato cannot be produced due to either heat or frost risks and/or extreme droughts or water logging. Heat and frost prone areas in levels not tolerated by the potato crop were removed using masks. The masks consisted of retaining areas with minimum and maximum temperatures ranging from 0 to 30 °C, during at least four consecutive months. The cumulative rainfall for those consecutive months had to be within 300 and 800 mm for a pixel to be retained as a rain-fed potato producing area. Areas with adequate temperature but limited rainfall were incorporated assuming irrigation water is at least partially available. At some sites potato production was not possible and a global geo referenced potato distribution was used to remove these areas (http://research.cip.cgiar.org/confluence/display/wpa/Home).

Results

The results of the simulated yields were expressed in tons of fresh matter per hectare. The simulated yield was classified into four classes, low (20-30 t ha^{-1}), medium (30-40 t ha^{-1}), high (40-50 t ha^{-1}), and very high (> 50 t ha^{-1}). Although maximum yield can be achieved in most regions of the world, temperate areas stand out as the more homogeneous. Cool tropics and subtropics are variable (Figure 1). This variability seems to be explained by climate anomalies. It is noteworthy that African highlands seem to be more homogeneous than the Andean highlands, variations that correspond to wider temperature amplitudes in the Andes that confer more variability to the simulation of potential productivity. It is then hypothesized that biotic factors explain better the gap between potential and attainable yields in African highlands whereas in the Andes abiotic factors seem to be limiting under actual conditions.

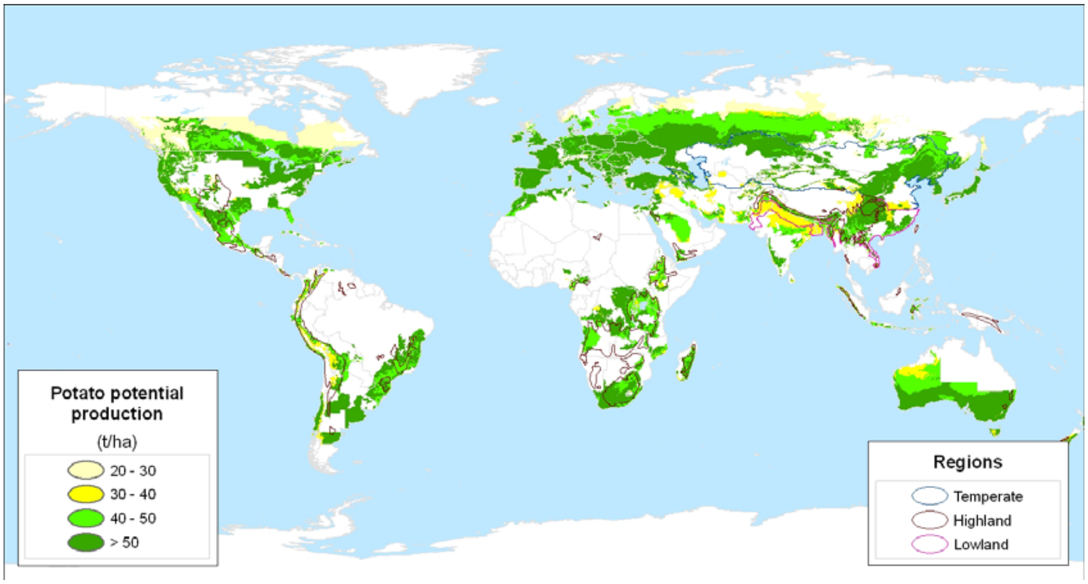

Figure 1. Potato global productivity limited by radiation and temperature, estimated with the Solanum model using the physiological parameters for *S. tuberosum spp. tuberosum*

Single versus double growing seasons

Double growing season areas were predominantly located in the highlands and subtropical lowlands, while in temperate regions a single growing season dominated (Figure 2).

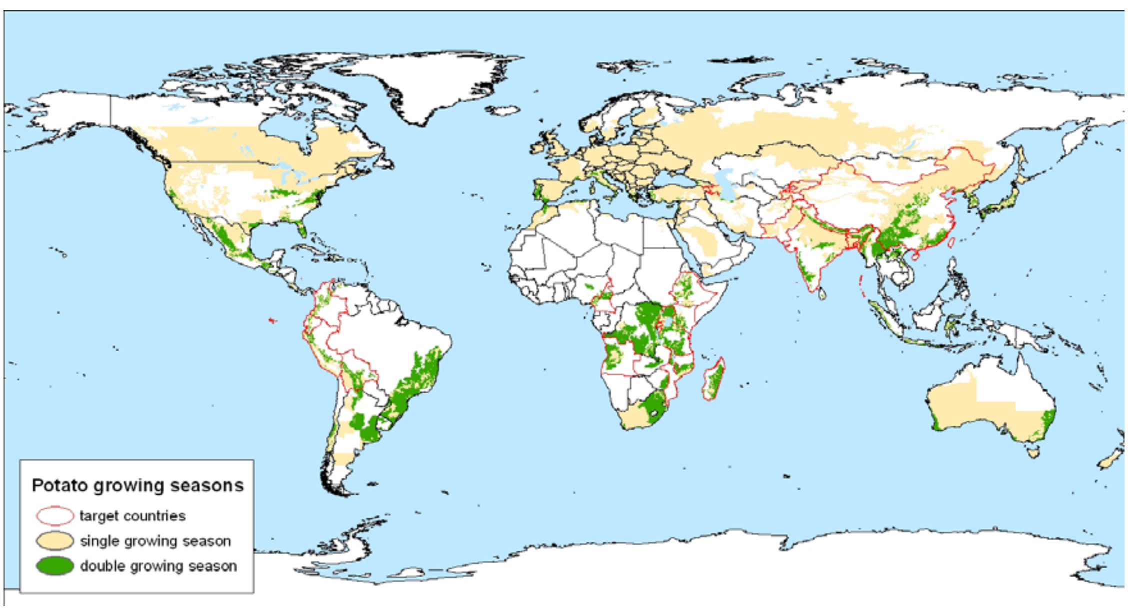

Figure 2. Growing seasons identified using the GeoSolanum model

Effect of the use of a frost tolerant potato cultivar

The analysis of the change in productivity was assessed using a frost tolerant potato cultivar in target countries and regions. This effect was quantified in areas where the minimum temperature is between 0 and 2°C, which are specially located in the highlands of South America and temperate regions. In this region the simulated yield could increase from 1 to 25% (Figure 3).

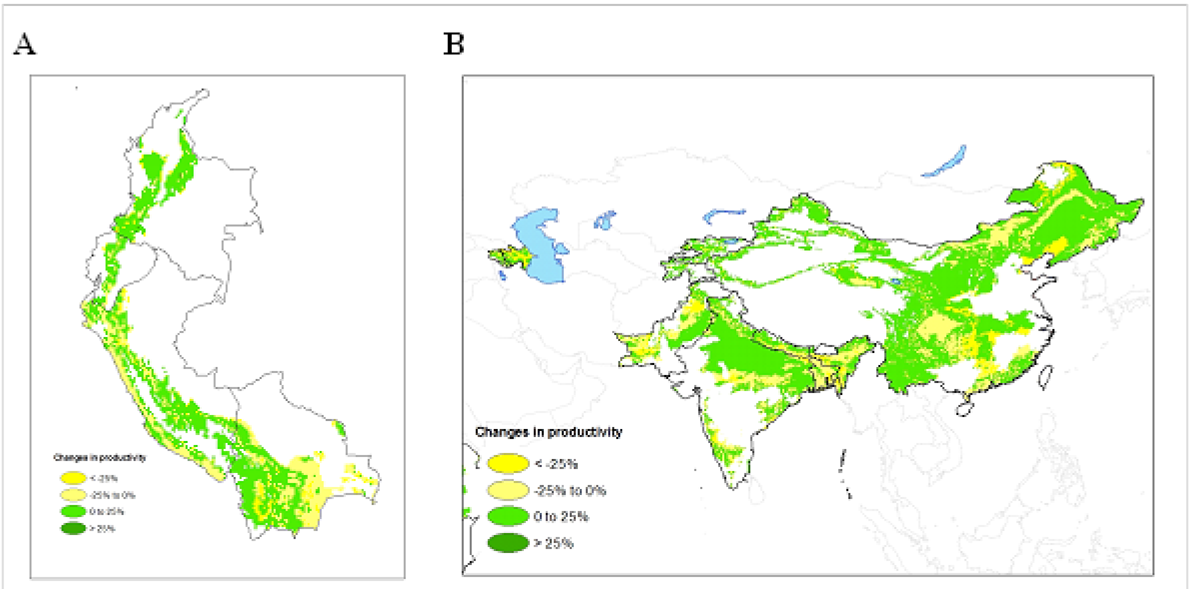

Figure 3. Changes in productivity due to the use of a frost tolerant potato cultivar in target countries of South America (A) and Asia (B).

Discusion

The GeoSolanum model is a flexible tool parameterized with physiological parameters of *S. tuberosum*, *S. andigena*, *S. ajanhuiri*, *S. juzepczukki* and their hybrids. The model does not consider the photoperiod effect, but in the future this parameter could be included. After validating these parameters in target areas around the world different scenarios can be assessed to predict the possible impact of introducing new germplasm. Water and nitrogen routines are ready to be incorporated to also simulate attainable production in target regions. Better climate downscaling procedures to incorporate climate variability and change scenarios are also being developed at CIP. The present example shows how useful geospatial modeling tools can be for targeting intervention areas where CIP can contribute to the generation of food and income through its mandate crops. Although the present example was at a global scale, a similar approach can be followed for smaller areas at a much higher spatial resolution.

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