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Natural Resource Management among Small-scale Farmers in Semi-arid Lands: Building on Traditional Knowledge and Agroecology

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Abstract: Although risk and uncertainty dominate the lives of most rural inhabitants of the semi-arid regions of the world, many farmers have been able to develop durable farming systems through the use of innovative soil and water management systems and the use of locally adapted crop species and varieties. In this paper we provide examples of farming systems developed by traditional farmers well adapted to the local conditions of the semi-arid environment, enabling farmers to generate sustained yields meeting their subsistence needs, despite harsh conditions and low use of external inputs. Part of this performance is linked to the ingenious soil and water conservation systems but also to the high levels of agrobiodiversity exhibited by traditional agroecosystems, which in turn positively influences agroecosystem function. We also give examples of projects aimed at assisting rainfed resource-poor farmers in the development of a variety of practical techniques and strategies to enhance production and resiliency in the midst of resource constraints typical of semi-arid environments. Many of these efforts use elements of modern science but that build upon traditional knowledge by including farmers in the development process.

Key words: Traditional knowlecge, agroecology, water management, natural resources.

Throughout the semi-arid lands of the developing world, small scale, resource-poor farmers who manage such risk prone and marginal environments, remain largely untouched by modern agricultural technology. Although risk and uncertainty dominate the lives of these rural inhabitants, many farmers have been able to develop durable farming systems through the use of innovative soil and water management systems and the use of locally adapted crop species and varieties (Barrow, 1999). Based on ecological rationale and by manipulating nature indirectly (i.e., concentrating scarce rainwater as well as through provision of supplementary water during critical times) farmers perform small-scale management of the local environment which moderates natural vagaries allowing them to obtain a sustainable harvest from the land, even in the midst of drought. These indigenous and ingenious innovations provide a source of inspiration for agricultural development; in fact a series of novel agroecosystem designs promoted by NGOs and researchers have been modeled after successful traditional farming systems (Reij and Waters-Bayer, 2001).

Clearly, the historical challenge to enhance food security in the semi-arid regions of the developing world, is to increase food production in the marginal dryland areas where a great mass of poor people are concentrated. The study of traditional forms on natural resource management and the ways in which peasants maintain and use biodiversity in such harsh environments can considerably speed the emergence of agroecological principles, which are urgently needed to develop more sustainable agroecosystems and agrobiodiversity conservation strategies in the semi-arid regions of the world (Dewalt, 1994; Altieri, 2004)

In this paper we provide examples of farming systems developed by traditional farmers well adapted to the local conditions of the semi-arid environment, enabling farmers to generate sustained yields meeting their subsistence needs, despite marginal land endowments and low use of external inputs (Browder, 1989; Wilken, 1987). Part of this performance is linked to the ingenious soil and water conservation systems, but also to the high levels of agrobiodiversity exhibited by traditional agroecosystems, which in turn positively influences agroecosystem function (Altieri, 1995). We also give examples of projects aimed at assisting resource-poor farmers in the development of a variety of practical techniques and strategies to enhance production and resiliency in the midst of resource constraints typical of semi-arid environments. These efforts have required that researchers and NGO technicians redirect ecological research to be more problem solving and more participatory so that it is relevant to rural people. As discussed later, most proposed agroecological strategies tend to be applicable under the highly heterogeneous and diverse conditions in which semi-arid smallholders live. Proposed interventions are environmentally sustainable and based on the use of local resources combining indigenous and appropriate external knowledge. The emphasis lies on improving whole farming performance and productivity rather than the yield of specific commodities.

Building on Traditional Knowledge

A logical starting point in the development of new pro-poor agricultural development approaches are the very systems that traditional farmers have developed and/or inherited through generations in areas of limited rainfall. Such complex farming systems, adapted to the local conditions, have helped small farmers to sustainably manage harsh environments and to meet their subsistence needs, without depending on mechanization, chemical fertilizers, pesticides or other technologies of modern agricultural science (Klee, 1980; Denevan, 1995). Although many of these systems have collapsed or disappeared in many parts of the Third World, the stubborn persistence of millions of hectares under traditional agriculture in the form of raised fields, terraces, polycultures, agroforestry systems, water harvesting systems, etc., are example of a successful indigenous agricultural strategy and comprises a tribute to the “creativity” of small farmers throughout the developing world. These microcosms of traditional agriculture offer promising models for other areas as they promote biodiversity, thrive without agrochemicals, and sustain year-round yields (Brokenshaw *et al*., 1980).

Traditional farming systems commonly support a high degree of plant diversity in the form of polycultures and/or agroforestry patterns, and in the semi-arid regions such systems are possible due to ingenious soil and water management systems developed by farmers. The strategy of minimizing risks by conserving soils, harvesting water and planting several species of plants and varieties of crops, stabilizes yields over the long term, promotes diet diversity and maximizes returns even under low levels of technology, limited resources and water stress. The following three examples highlight the creativity of traditional farmers living in semi-arid regions, and the ecological complexity that underlies such traditional innovations.

Southern Tunisia

In southern Tunisia as in most semi-arid ecosystems, crops have historically been at risk from physiological drought and so rainwater must be collected, concentrated and transferred to cropped areas quickly to minimize losses via evaporation and runoff. Such macrocatchment rainwater harvesting has a long history in the Matmata Plateau (Hill and Woodland, 2003). Here, climate, topography and soils together make rainwater harvesting very effective. The majority of rain falls as high-intensity, low-frequency downpours. Overland flow is generated rapidly and it travels quickly over the steep slopes, supplying water and soil to valley bottoms. Earthen check dams (tabias-strengthened by dry stone retaining walls)) are sited progressively downslope to arrest material eroded from the valley sides and this sediment is levelled to form agricultural fields (jessour). Water that is trapped behind these dams after rains infiltrates into the soil and it can create a local, albeit temporary, phreatic water supply. The rainfall multiplier effect of rainwater harvesting depends primarily on the ratio of catchment area to cropped area. This ratio is typically between 2:1 and 10:1 in southern Tunisian macrocatchments. To the west of Matmata, a ratio of 6:1 translates into field sizes approximating 0.6 ha and catchment sizes of around 4 ha, varying slightly with site, topography and capability of the builders. If infiltration and evaporation losses are prevented, 10 mm of rain falling on a 1ha semi-arid catchment can yield around 100,000 L of water.

Using these methods, today most farmers in Matmata practice agroforestry on the jessour. In 3 ha size fields they are able to grow relatively demanding trees such as olives, figs, almonds, pomegranates and date palms. Annual crops include barley, peas, lentils and beans, and fodder crops such as alfalfa. These parcels are often dispersed following the natural occurrence of water in the landscape, so fragmentation of holdings is a common feature.

Rainwater harvesting in the region remains largely decentralized in nature. Sites are managed on a collective and community basis following local custom and enforced by Islamic law. Under such systems, water is considered as a communal property, with just enough consumed to meet community needs without wastage. Local expertise is anchored in an awareness of the reciprocal relationship between surface water and groundwater. Almost all farmers are aware of the necessity of replenishing what they termed loosely as underground water supplies in order to ensure water for community use in future seasons. Rainwater harvesting on hillsides helps to increase infiltration and hence recharge groundwater, which is drawn upon locally and in the lower catchments (**Fig. 1**). Land units are integrated effectively with respect to hydrology, allowing equitable use of water over space and, crucially, replenishing long-term stores (Hill and Woodland, 2003).

Vernacular knowledge and craftsmanship, derived from centuries of interaction with the local environment, has been used to equip tabias with different types of overflow. These promote effective water distribution and allow a certain flexibility against climatic extremes. Lateral overflows are employed in 60% of tabias in the Matmata Hills. These are purpose-made breaches in the earthen bunds at valley sides. Simple lateral overflows are carved out of the soil, their earthen floors resting at the same height as the up-slope terrace. They permit excess water to flow by gravity onto the terrace below, ensuring irrigation water with minimal erosive capability. Erosion of the overflows themselves is often reduced by strengthening their floors and sides with stones. Central overflows have been observed within 38% of tabias in the Matmata Hills. These require greater manpower and more materials to construct when compared with lateral overflows. Dry

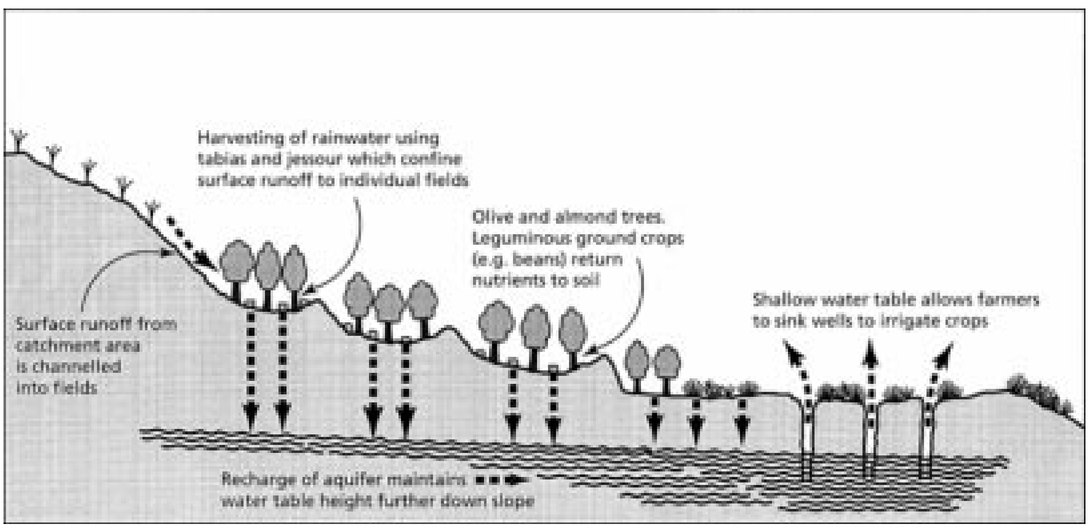

Fig. 1. Traditional water harvesting in agroecosystems of Tunisia (Hill and Woodland 2003).

stone or cement walls retain the earth of the tabia and the overflow floor is stepped downslope to dissipate the energy of escaping water (Reij *et al.*, 1996).

The height of tabia overflows ensures that cropped fields downslope are not deprived of water by higher fields. Equally, the height of the overflow prevents the build up of too much water after storms such that the root zone remains waterlogged for long periods. This enhances agricultural potential by increasing root aeration, and reducing soil salinization because water infiltrates efficiently and is used rapidly by crops. The water table resides at depth, ensuring that salts are not brought to the surface by water table rise. Appropriate tabia construction reduces the chance of breaching and soils being washed downslope by headward erosion.

The Papago and other indigenous peoples of semi-arid North America

In the semi-arid zones of North America, in which water is the principal limiting factor, the experiences of the indigenous Seri, Pima, Papago and other indigenous groups offer local options for rainfed agriculture. These cultures have made resources of a multitude of desert species with high nutritive content that can form the basis for an agriculture appropriate to these zones. Some of them have developed agricultural techniques, which utilize floodwater on a small scale, with hand-made canals, terraces, berms and diversions for the retention and utilization of rainwaters (Nabhan, 1979).

Floodwater farming is the management of a sporadic flashfloods for a crop production. It is an ancient technique in the southwestern regions of North America that is currently being revaluated. Agronomically productive conditions have been developed by geomorphological alterations of the floodplain, including canals, terraces, grids, spreaders, and weirs. These environmental modifications serve to concentrate the runoff from a large watershed into a strategically located field, and break the erosive force of the incoming water. In addition, native Americans manipulate the wild and weedy flora of floodwater fields by discouraging or protecting and harvesting selected species (Nabhan, 1979).

In Arizona, the Papago and other native cultures of the Sonora desert historically sought alluvial fans (low valleys where floodwaters and the organic matter they carry concentrate) for establishing productive fields producing crops adapted to the semi-arid conditions such as coyote gourd, desert amaranthus, tepary beans, devil's claw and a variety of succulents, cacti and herbaceous perennials.

Living in a Sonoran Desert area of 150-350 mm mean annual rainfall, the Papago have traditionally irrigated their floodplain fields with the stormwaters of intermittent water-courses, or arroyos (Nabhan, 1982). In the desert, there are usually no more than 3-15 substantial storm events during the year; of these, typically no more than 5-6 are sufficiently large to stimulate a spurt of plant production.

In one Papago community, 100 families maintained 355 ha of crops on farms receiving storm water, organic matter and nutrients from 240 km of watershed. With a single intense storm, enough nitrogen-rich litter from leguminous tress, rodent feces and other decomposed detritus from the uplands, is shed onto the alluvial fans to add as much as 30 m^3 of organic material to each hectare (Nabhan, 1982). In addition to 50 day maize, Tepary beans (*Phaseolus acutifolius* var. latifolius) is the most nutritionally important crop of Papago indians. Teparies are a heat and drought adapted crop of the Papago, and historically the most important protein and mineral source (Nabhan *et al*., 1981). Their mean protein contents and seed yields per plant tend to be higher in Papago flashflood fields than in modern irrigated counterparts. Unfortunately, traditional Papago indian floodwater farming today is a threatened agricultural ecosystem.

The traditional Papago agricultural system presents a different food production strategy than most groundwater-based systems introduced into arid lands. Responding to sparse, irregular water availability in the desert, the Papago produce crops (principally tepary beans, corn, squashes and others) which grow quickly enough to avoid mortality due to prolonged drought. They deal with the uneven spatial distribution of stormwaters by concentrating into small fields; and utilizing several fields, each spatially separated from the others. Within each filed/field, mixed plantings occur with wide spaces between plants, a risk-minimizing tactic. In general, Papago farming families have seldom been willing to "force" a single field to produce more through intensifying manipulation or by concentrating their efforts on a single plant resource. The Papago strategy seeks more dependable seed yield for the water available, but not necessarily per unit land. Since water, not land, is the limiting factor in the deserts, this strategy has adaptive value (Nabhan, 1982).

Figure 2 depicts a model desert agroecosystem for the Papago region where a mixture of species are planted to partition environmental resources (especially water) more efficiently in time and space. The benefits of such diverse mixture is expected to be greater under suboptimal conditions where high yielding genotypes would experience stress and low performance.

The Otomì of Valley of Mezquital, Mexico

The Mezquital Valley, which is part of the Central Mexican Highlands, has been inhabited by people of the Otomí or Hñähñü ethnic group since at least ..the pre-Columbian period Fournier ....). establishing permanent settlements based on rainfed agriculture and sometimes even built water-harvesting structures.

The area, which is one of the poorest and most marginalized regions of Mexico, shows how people can survive using unusual food sources. The Mezquital valley exhibit several limiting ecological conditions, especially its infertile calcareous soils and scarcity of water. This environment conditioned the relationships between the Otomí and its surrounding landscapes, specially in the perception and use of habitats, water resources, soils and plant species.

According to the studies of Johnson (1977), the natural resources management used by the Otomì people reflect a level of diversified production adapted to the different landscapes of the Mezquital Valley as well as an emphasis on rainy-season agriculture and the intensive use of maguey

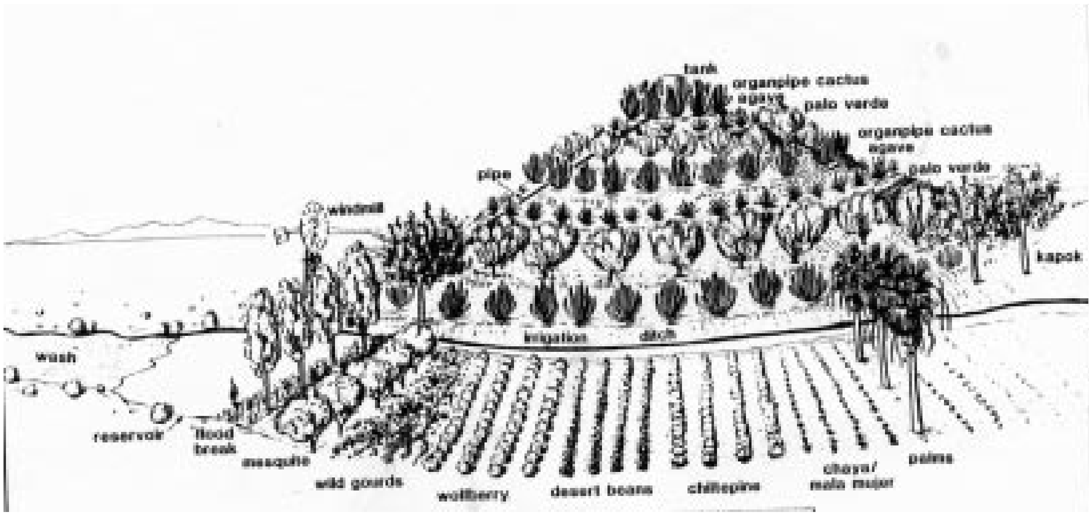

Fig. 2. A model agroecosystem that emphasizes water harvesting for the Sonoran desert (Nabhan 1982)

(*Agave* spp.). Maguey species are used to produce fiber for making cordage and clothing, cooked flesh and especially pulque, a mildly alcoholic beverage formed by the natural fermentation of the sugary sap that these plants produce (Parsons and Parsons, 1990). In addition, maguey species are also used as key plants in the management of soils during the construction of terraces to avoid erosion.

Otomì people distinguish three classes of landscape units: the cerro, the lowland and the hill. The cerro, which normally is a communal land, is covered with wild vegetation (shrublands) used to feed animals and for hunting and gathering. People also use the lowest portions of the cerro to build houses. Most of the agricultural fields are on the hills and lowlands. Otomì farmers recognize three types of hills to cultivate: gullies (barrancas), slopes (laderas) and flat lands (planes), and on the two classes of lowlands (gullies and flat lands). During the wet season, water washes away soil from the slopes and gullies of the hills to the lowlands, to deposit it on the low flatlands. Thus, lowlands are the areas to which all water flows and sediments accumulate (Johnson, 1982).

With a detailed knowledge of soils, relief, vegetation and water movements, Otomì people build *bordos* to trap the rainwater and build up the soil with the sediments it brings. The best place for a bordo is right in the path of the water that is the gully itself. This kind of bordo is called *atajadizo*. Farmers also build bordos on the hillside. It takes six or seven rainstorms to get a crop (generally maize and beans) on hillside bordos and atajadizos. They normally are placed along the contours in order to take the best advantage of the water flow. The placement of stones and plants of maguey are crucial during the construction of bordos, and fields are recurrently fertilized with manures to improve the soil. Organic fertilizers consist of mixtures of goat, sheep and cow manures, household trash, ashes, dry plants and soils from other terrain (Johnson, 1977).

Agroecology as a Fundamental Scientific Basis for NRM

Agroecology is a science that provides guidelines to understanding the nature of agroecosystems and the principles by which they function. Agroecology provides the basic ecological principles for how to study, design and manage agroecosystems that are both productive and natural resource conserving, and that are also culturally sensitive, socially just and economically viable.

Instead of focusing on one particular component of the agroecosystem, agroecology emphasizes the interrelatedness of all agroecosystem components and the complex dynamics of ecological processes including all environmental and human elements. It focuses on the form, dynamics and functions of their interrelationships and the processes in which they are involved. An area used for agricultural production, e.g. a field, is seen as a complex system in which ecological processes found under natural conditions also occur, e.g., nutrient cycling, predator/prey interactions, competition, symbiosis, successional changes, etc.

Ecological concepts are utilized to favor natural processes and biological interactions that optimize synergies so that diversified farms are able to sponsor their own soil fertility, crop protection and productivity. By assembling crops, animals, trees, soils and other factors in spatial/temporal diversified schemes, several processes are optimized. Processes such as organic matter accumulation and decomposition, water retention, nutrient cycling and pest regulation are crucial in determining the sustainability of agricultural systems (Altieri, 1995).

Agroecology takes greater advantage of natural processes and beneficial on-farm interactions in order to reduce off-farm input use and to improve the efficiency of farming systems. Technologies emphasized tend to enhance the functional biodiversity of agroecosystems as well as the conservation of existing on-farm resources. Promoted technologies such as cover crops, green manures, intercropping, agroforestry and crop-livestock mixtures are multi-functional as their adoption usually means favorable changes in various components of the farming systems at the same time.

Most of these technologies may function as an "ecological turntable" by activating and influencing components of the agroecosystem and processes such as:

- Recycling of biomass and balancing nutrient flow and availability.
- Securing favorable soil conditions for plant growth, through enhanced organic matter and soil biotic activity.
- Minimizing losses of solar radiation, air, water and nutrients through microclimate management, water harvesting and soil cover.

- Enhancing species and genetic diversification of the agroecosystem in time and space.
- Enhancing beneficial biological interactions and synergisms among agrobiodiversity components resulting in the promotion of key ecological processes and services.

At the heart of the agroecology strategy is the idea that an agroecosystem should mimic the functioning of local ecosystems thus exhibiting tight nutrient cycling, complex structure, and enhanced biodiversity. The expectation is that such agricultural mimics, like their natural models, can be productive, pest resistant and conservative of nutrients. The ecosystem-analog approach is the basis for the promotion of polycultures and agroforestry systems that imitate biodiverse successional vegetation, which exhibit low requirements for fertilizer, high use of available nutrients, and high protection from pests. Part of this performance is linked to the high levels of agrobiodiversity exhibited by traditional agroecosystems, which in turn positively influences agroecosystem function (Altieri, 1995).

The benefits of diversity in semi-arid cropping systems

Many agricultural studies have shown that complex, multi-species agricultural systems are more dependable in production and more sustainable in terms of resource conservation than simplified agro-ecosystems. Significant yield increases have been reported in diverse cropping systems compared to monocultures. Enhanced yields in diverse cropping systems may result from a variety of mechanisms, such as more efficient use of resources (light, water, nutrients) or reduced pest damage (Francis, **1986 or 1998**). The mechanisms that result in higher productivity in diverse agroecosystems are embedded in the process of facilitation. Facilitation occurs when one crop modifies the environment in a way that benefits a second crop, for example, by lowering the population of a critical herbivore, or by releasing nutrients that can be taken up by the second crop. Facilitation may result in over yielding even where direct competition between crops is substantial. Ecological studies suggest that more diverse plant communities are more resistant to disturbance and more resilient to environmental perturbations like drought. In agricultural situations this means that polycultures exhibit greater yield stability and less productivity declines during a drought than in the case of monocultures and relative differences in productivity between monocultures and polycultures became more accentuated as stress increased (Vandermeer, 1981).

Natarajan and Willey (**1986 or 1996**) examined the effect of drought on enhanced yields with polycultures by manipulating water stress on intercrops of sorghum (*Sorghum bicolor*) and peanut (*Arachis* spp.), millet (*Panicum* spp.) and peanut, and sorghum and millet. Although total biomass production in both polycultures and monocultures decreased as water stress increased, all of these intercrops yielded consistently at five levels of moisture availability, ranging from 297 to 584 mm of water applied over the cropping season. Quite interestingly, the rate of over yielding actually increased with water stress, such that the relative differences in productivity between monocultures and polycultures became more accentuated as stress increased.

Much research has shown that increasing plant diversity in agroecosystems leads to reduced herbivorous insect abundance (Altieri and Nicholls, 2004). Insect pest species usually exhibit higher abundance in monoculture than in diversified crop systems. scientists at the International Center of Insect Physiology and Ecology (ICIPE) in Kenya, Africa, developed a habitat management system which uses two kinds of crops that are planted together with maize: a plant that repels these stemborers (the push) and another that attracts (the pull) them (Khan *et al*., 1998). The push-pull system has been tested on over 450 farms in two districts of Kenya and has now been released for uptake by the national extension systems in East Africa. Participating farmers in the breadbasket of Trans Nzoia are reporting a 15-20% increase in maize yield. In the semi-arid Suba district – plagued by both stemborers and striga – a substantial increase in milk yield has occurred in the last four years, with farmers now being able to support grade cows on the fodder produced. When farmers plant maize together with the push-pull plants, a return of US$ 2.30 for every dollar invested is made, as compared to only $1.40 obtained by planting maize as a monocrop.

Two of the most useful trap crops that pull in the borers' natural enemies such as the parasitic wasp (*Cotesia sesamiae*), are napier grass (*Pennisetum purpureum*) and Sudan grass (*Sorghum vulgare* sudanese), both important fodder plants; these are planted in a border around the maize. Two excellent borer-repelling crops which are planted between the rows of maize are molasses grass (*Melinis minutifolia*), which also repels ticks, and the leguminous silverleaf (*Desmodium*), which in addition can suppress the parasitic weed *Striga* by a factor of 40 compared to maize monocrop. Desmodium's N-fixing ability increases soil fertility; and it is excellent forage. As an added bonus, sale of *Desmodium* seed is proving to be a new income-generating opportunity for women in the project areas.

Many farmers in the semi-arid regions relay on manures and crop residues to fertilize their polycultural fields. Such additions of organic matter play a key part in local and regional water cycles due to its role in promoting water infiltration into soils and storage within soils. Soils high in organic matter enhance rapid infiltration, making water available to plants to use or percolating deep into the subsoil to help recharge the groundwater supply. Evidence increasingly shows that organic farmers who build soil organic matter content suffer less of an impact during severe dry spells than conventional farmers who do not use compost or legumes (Magdoff and van Es, 2000).

Capturing Water in a Variable Environment

Semi-arid regions are characterized by low erratic rainfall, poor nutrient soils and high temperatures and pose serious limitations in crop productivity especially when water supply is inadequate. This can be manifested through poor development of crop yield structures and ultimately low yields. Semi-arid areas have at least one entirely rainless month/year and the amount of rainfall ranges from 500-1000 mm/annum in most areas. This means that conditions of water deficit, water stress or drought are common in these areas. In cases of extreme drought stress, crops yield poorly or not at all if drought stress during reproductive growth is severe and persistent (Barrow, 1999).

Changes in severity of drought contribute to dry land degradation and desertification. This process has been evident in the Sahel region (West Africa) where rainfall levels have declined by 20-40% in recent decades accompanied by severe land degradation.

The amount of rainfall that can be effectively utilized for crop growth in these lands is also low. This effective rainfall however, can be increased through water harvesting.

In Sub-Saharan Africa, 40% of the farmland is located in semi-arid and dry sub Humid savannahs. Despite the frequent occurrence of water scarcity, in most years there is more than enough water to potentially produce crops. The problem is that large volumes of water are lost through surface runoff, soil evaporation and deep percolation. The challenge is how to capture that water and make it available to crops during times of scarcity (Reij *et al.*, 1996).

There is a number of soil and water conservation initiatives throughout the semi-arid world, some promoted by NGOs and/or non-government organizations and many as the result of farmers innovations. NGO or researchers promoted initiatives Throughout Africa, Asia and Latin America there are many NGOs and/or researchers-extensionists involved in promoting agroecological initiatives that have demonstrated a positive impact on the livelihoods of small farming communities in various countries. Success is dependent on the use of a variety of agroecological improvements that in addition to enhance farm diversification, favor a better use of local resources and improve human capital enhancement and community empowerment through training and participatory methods.

NGO-research centers promoted initiatives

Africa: In north-western Tanzania the Soil Conservation and Agroforestry Pilot Program established a program to make available conservation tillage systems for small farmers. The systems still minimize the disturbance of the soil, but by using animal drawn rippers and subsoilers, farmers open part of the soil for rainfall infiltration and also a system of conservation farming using hand hoes to dig small planting pits. (Mwalley and Rocktrom, 2003).

In many cases farmers used *Dolichos lablab* as a cover crop which in addition to fixing nitrogen, produces beans that are sold in the market. Ripping proved to be the preferred system because it enables land preparation before the onset of rains - a critical opportunity in semi-arid regions where 25% of a season's rain may fall during the first rainstorms. Therefore conservation farming systems were dry planted, with manure applications and manufacture rock phosphate in the permanent ripped planting lines. Manual pitting resulted in approximately the same maize yield as the animal drawn system (3, 5 t ha^{-1}), but in general the adoption of these conservation systems meant a 240% yield increase for farmers. Manual pitting is cheap, does not require oxen or new implements and above all gave farmers full control over precious inputs such as seed, manure and labor.

The rainwater harvesting effect of the conservation farming systems was obvious when calculated based on the amount of crop produced per drop of water. In the conventional tillage system only 2, 6 kg of grain are produced per mm of rainfall, compared to 7.4 kg mm^{-1} of rainfall for the conservation farming system (Mwalley and Rocktrom, 2003).

Mexico "Water Forever" Program of the Mixteca Region: The Mixteca region, covering parts of the states of Puebla, Oaxaca and Guerrero, is 40,000 km^2 of irregular, mountainous terrain with low, unevenly distributed precipitation (300 to 700 mm/year). Covered by typically semi-arid vegetation, dominated by shrubs and cacti, the area has been inhabited for about 7,000 years. It is thought that in this inhospitable terrain, using the available water plants like maize were domesticated and agriculture was born in Mesoamerica. Today, it is inhabited by mainly indigenous peoples from at least seven different ethnic groups: the Nahuas, Mixtecs, Popolocs, Ixcatecs, Mazatecs, Cuicatecs and Chinantecs. It is one of Mexico's poorest agricultural regions, with high levels of marginalization and, therefore, a considerable number of its inhabitants are forced to migrate.

Undoubtedly, the Mixteca's most serious problem is water. The World Health Organization has established an international standard stipulating that each individual needs 150 L of potable water a day, while the World Bank puts the figure at 50 L a day. Average water consumption in Mexico City, for example, is 335 L per person per day, rising to around 1,000 L in wealthier neighborhoods and dropping to only 28 in the poorest areas. In the Mixteca, many families survive with only 7 L a day, that is, one-fourth of the consumption of the poorest of the poor in Mexico. Paradoxically there is a long history of water management and use in the Mixteca region, records of the first water management techniques date from 2,800 years ago. Today, the population still has hydro-geological ad hydro-agricultural knowledge of inestimable value.

The technological option that the "modern world" offers for obtaining abundant water is drilling deep wells, which is expensive and has serious ecological limitations given the nature of the geological substrata (for example, volcanic or metamorphic rock) in many parts of the Mixteca region with a low potential for accumulated underground moisture. On the other hand, the combined action of deforestation and over-grazing has removed the layer of natural vegetation that covered the sides of hills and mountains, which has in turn meant that rainwater does not filter down to the subsoil to feed underground water; rather, it runs over the surface causing erosion. But the main limitation is economic: drilling a deep well costs between US $ 25,000 and US $ 40,000, a sum completely out of the reach of the Mixteca's peasant population.

Given all the above constraints, the project "Water Forever" was created in 1988 by an NGO called Alternativas y Procesos de Participación Social, AC (Social Participation Alternatives and

Processes). The project covers the northern most area of the Mixteca, on the borders of the Mexican states of Puebla and Oaxaca and including a large part of the Tehuacán Valley, reaching about 200,000 inhabitants in approximately 100 rural communities (Toledo and Solis, 2001).

The program considered the history of water management in the region essential to its activities, focusing on the urgent need to create solutions not only for the short term, but also taking into account the environmental problems implicit in the loss of underground water supplies and the soil erosion that made the regional situation increasingly critical.

This project considered that water scarcity is influenced by population increase, inappropriate use of natural resources and unequal access to available water, unjustly concentrated in the hands of a few individuals and power groups.

In this way, the project recognized that the root of the problem did not lie only in obtaining water to satisfy different needs, but also in both ensuring that the extraction of water not deplete underground supplies and that access to be fair to the different groups of society. With this focus, the project has developed by 2001, 508 hydraulic works in communities in the region, benefiting between 77,000 and 134,000 inhabitants. Harvested water is used at the household level to domestic use, animal subsistence and principally subsistence agriculture, which produces maize, beans and amaranth. The strategy is directed at the ecological restoration of the watershed with a number of techniques to effectively harvest water and conserve soils for sustainable production (**Fig. 3**).

Its activities have received significant support both from Mexican government agencies and private organizations and foundations. It has also designed, tested and perfected an applied research model that has turned out to be useful, new, original and very important.

For 20 years, Alternatives has worked with four of the most important challenges facing contemporary science in solving rural poverty: (a) the recognition of the ecological or biological region (bio-regionalism); (b) participatory research; (c) an interdisciplinary focus; and, finally, (d) technological diversity. Both Alternatives' organizational structure and its research and technical team are an expression of this four-sided theoretical and methodological thrust.

The main management units are the basins, which are delimited thanks to the use of a geographic informational system generated by its personnel, with water as the crosscutting issue. Its research, social field work and development of hydrological works are based on this bioregional unity. To get people to perceive bio-regional unity, Alternatives fosters participatory research that leads to a micro-regional topological view and which favors collaboration among up and downstream communities and families.

With this methodology, also know as participatory natural resources management, the works proposed are based on the history of the region itself. Therefore, in addition to recuperating traditions, the work enriches them by applying new techniques and equipment to make them more easily accepted. In practice, it is a process of recovering the collective memory of water

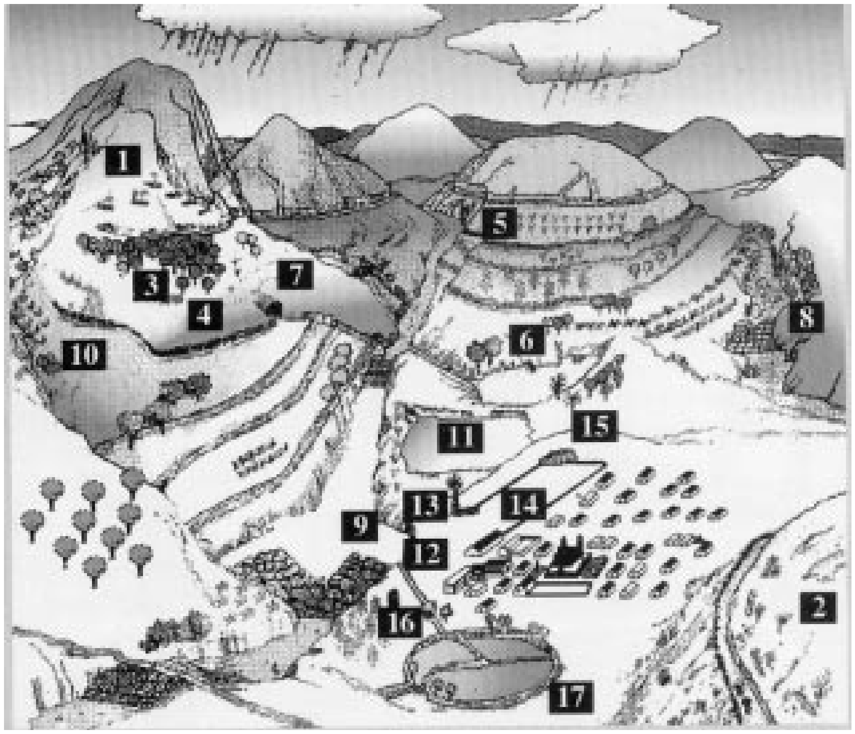

Fig. 3. Harvesting water through watershed regeneration in the Mixteca Region, Mexic To regenerate the Mixteca Region‘s basins, specific treatments are applied on the hills, knolls, valleys and ravines using different technologies. The work begins on the hills with retaining devices that includes ditches and trenches (1), water harvesting ring (2), reforestation (3) and contour lines with vegetation (4). On the rises where the slopes is less than on the hills, borders, terraces (5) earthen dikes (17) and watering holes (6) can be built, making it possible to water cattle and others animals or irrigate corps. If we take into account that ravines have been formed where water has most easily eroded the soil, it can be regenerated by building rock seeping dams (7) or gabion seeping dams (8). These works slow the speed and force of the initial flow with provisional water stagnation and soil retention, thus achieving control over the two natural resources involved, soil and water. The water obtained from buildings dams can be utilized by building shallow wells (16), seeping galleries and diversion dams (9) that channel part id the flow of water to agricultural land. In addition, the water in the high parts of the basins replenishes existing springs (10). One water has been gathered, irrigation systems (11) are designed as wall as water storage systems that prevent its filtering and evaporating and make it available to distribute to the communities. The water can be transported to where it is used by earth- filled canals (12), unlined or lined with cement or stone. Nevertheless, the transportation of piped water (14) is the most efficient way to avoid both filtration and evaporation. Before laying the pipes, it is necessary to construct a tank (15) where the different particles in the water with settle to avoid clogging. For this work, operating costs can be cut by using alternative energy, like windmills (13) or manual pumps that will finally distribute the water to the population. After Hernàn-dez-Garciadiego and Herrerìas, 1998.

management and use, something left out of the "normal" forms of doing science today, and one of its most serious limitations.

If the problem of water in the Mixteca were looked at as an isolated phenomenon, the final result would be reduced to simply building a few dams or drilling some deep wells, a matter restricted to geologists and engineers. The focus used in these projects, however, considers the hydrological problem part of a bio-region (the basin) and takes into account the hydro-geological experience accumulated for centuries by the local cultures, thus demanding the integration of the different disciplines and the creation of multidisciplinary teams of professionals.

The last original contribution lies in the implementation of a broad spectrum of designs to supply water to the communities. This leads to a redefinition of the very concept of technology, which ends up being framed in the historically determined cultural values of the communities and by the ecological conditions of different regions (basins).

For this reason, the technological solutions adopted include pre-hispanic, colonial and modern technologies, or a mix of the three, creating "hybrid technologies".

More than two decades of intensive work has allowed the refinement of both the social promotion methodologies and the institutional environment that supports it. With the design of an innovative-participatory approach the goal has been the development of water resources for improving the livelihoods of the poor. Linked to this ecological development, an important commercial development has been also achieved, bringing to the modern market, amaranth products produced with harvested water, under the Quali brand produced by 1,100 small farmers organized in 60 grassroot cooperatives (Toledo and Solis, 2001).

Farmers innovations

In Zimbabwe hundreds of dryland farmers have benefited from the water harvesting systems developed by one farmer, Mr. Phiri Maseko. Phiri's three hectare plot is located on the slope of a hill, immediately below, which is the homestead. One of the most important resources is a large granite dome, or ruware, above the plot. In an uncontrolled situation this rock could cause severe erosion by channelling a lot of water onto the farm below. Instead, the rock provides the main source of water for the trees, crops and household. Tiers of stonewall terraces catch and direct the flow of water so that it can sink into the soil and replenish the underground store (**Fig. 4**). The terraces trap the grass seeds and create swathes of protective vegetation. Silt traps ensure that the terraces do not get choked with sand. Most of the water is then channelled into a seasonal unsealed reservoir to encourage efficient infiltration of water into the soil rather than storing it on the surface. Some of the water can be siphoned into a storage tank made from bricks and plaster (Reij *et al.*, 1996)

In many parts of Burkina Faso and Mali there has been a revival of the old water harvesting system known as "*zai*". The *zai* are pits that farmers dig in rock-hard barren land, into which water otherwise could not penetrate. The pits are about

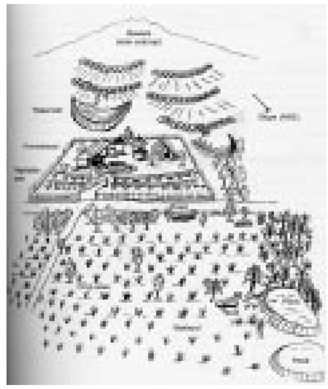

Fig. 4. A farming system cerated by a innovative dryland farmer in the semiarid of Zimbabwe

20-30 cm in deep and are filled with organic matter. This attracts termites, which dig channels and thus improve soil structure so that more water can infiltrate and held in the soil. By digesting the organic matter, the termites make nutrients more easily available to plants. In most cases farmers grow millet or sorghum or both in the zai. At times they sow trees directly together with the cereals in the same zai. At harvest, farmers cut the stalks off at a height of about 50-75cm, which protect the young trees from grazing animals. Farmers use anywhere from 9000 to 18000 pits per hectare, with compost applications ranging from 5, 6 to 11 t ha^{-1} (Reij and Waters-Bayer, 2001).

Over the years, thousands of farmers in the Yatenga region of Burkina Faso have used this locally improved technique to reclaim hundreds of hectares of degraded lands. Many farmers have been exposed to the improved zai the Zai school model established in the village of Somyanga by Mr Ousseni Zorome.

Farmers have become increasingly interested in the zai as they observe that the pits efficiently collect and concentrate runoff water and function with small quantities of manure and compost. The use of zai allows farmers to expand their resource base and to increase household security. Yields obtained on fields managed with zai are consistently higher (ranging from 870 to 1590 kg ha^{-1}) than those obtained on fields without zai (average 500-800 kg ha^{-1}).

Many farmers in the Dogon Plateau of Mali, a region where extreme drought periods with temperatures in excess of 40°C and evaporation rates of 250 mm/month, alternate with heavy and destructive rains, have reported similar benefits from the adoption of zai.

Applying Agroecology to Improve the Productivity of Small Farming Systems

Since the early 1980s, hundreds of agroecologically-based projects have been promoted by NGOs throughout the developing world, which incorporate elements of both traditional knowledge and modern agricultural science. A variety of projects conducted in the semi-arid regions feature resource-conserving yet highly productive systems, such as polycultures, agroforestry, and the integration of crops and livestock, etc. Such alternative approaches can be described as low-input technologies, but this designation refers to the external inputs required.

The amount of labor, skills, and management that are required as inputs to make land and other factors of production most productive is quite substantial. So rather than focus on what is not being utilized, it is better to focus on what is most important to increase food output, labor, knowledge and management (Uphoff, 2002).

Agroecological alternative approaches are based on using locally available resources as much as possible, though they do not totally reject the use of external inputs. However, farmers cannot benefit from technologies that are not available, affordable, or appropriate to their conditions. Purchased inputs present special problems and risks for less-secure farmers, particularly where supplies and the credit to facilitate purchases are inadequate (Altieri, 2002).

The analysis of dozens of NGO-led agroecological projects show convincingly that agroecological systems are not limited to producing low outputs, as some critics have asserted. Increases in production of 50 to 100% are fairly common with most alternative production methods. In some of these systems, yields for crops that the poor rely on most -rice, beans, maize, cassava, potatoes, barley – have been increased by several-fold, relying on labor and know-how more than on expensive purchased inputs, and capitalizing on processes of intensification and synergy.

A recent study of 208 agroecologically based projects and/or initiatives throughout the developing world, documented clear increases in food production over some 29 million hectares, with nearly 9 million households benefiting from increased food diversity and security. Promoted sustainable agriculture practices led to 50-100% increases in per hectare food production (about 1.71 mg per year per household) in rain-fed areas typical of small farmers living in marginal environments; that is an area of about 3.58 million hectares, cultivated by about 4.42 million farmers. Such yield enhancements are a true breakthrough for achieving food security among farmers isolated from mainstream agricultural institutions (Pretty *et al*., 2003).

More important than just yields, agroecological interventions raise total production significantly through diversification of farming systems, such as raising fish in rice paddies or growing crops with trees, or adding goats or poultry to household operations. Agroecological approaches increased the stability of production as seen in lower coefficients of variance in crop yield with better soil and water management. Agroecological initiatives where complemented by actions that tended to improve access to markets, credit and income generating activities. Analysts point at the following factors as underlying the success of agroecological improvements:

- Appropriate technology adapted by farmers' experimentation;
- Social learning and participatory approaches;

- Good linkages between farmers and external agencies, together with the existence of working partnerships between agencies;
- Presence of social capital at local level.

Scaling up of Agroecological Innovations

In most cases, farmers adopting agroecological models achieved significant levels of food security and natural resource conservation. Given the benefits and advantages of such initiatives, two basic questions emerge: (l) why these benefits have not disseminated more widely and (2) how to scale-up these initiatives to enable wider impact.

Obviously, technological or ecological intentions are not enough to disseminate agroecology. There are many factors that constraint the implementation of sustainable agriculture initiatives. Major changes must be made in policies, institutions, and research and development agendas to make sure that agroecological alternatives are adopted, made equitably and broadly accessible, and multiplied so that their full benefit for sustainable food security can be realized. This requires (a) changes in policies to stop subsidies of conventional technologies and to provide support for agroecological approaches, (b) appropriate equitable market opportunities including fair market access and market information to small farmers, (c) security of tenure and progressive decentralization processes and (d) increasing public investments in agroecological – participatory methods.

One important factor limiting the spread of agroecological innovations is that for the most part NGOs promoting such initiatives have not analyzed or systematized the principles that determined the level of success of the local initiatives, nor have been able to validate specific strategies for the scaling-up of such initiatives. A starting point therefore should be the understanding of the agroecological and socio-economic conditions under which alternatives were adopted and implemented at the local level. Such information can shed light on the constraints and opportunities farmers to whom benefits should be expanded at a more regional level are likely to face (Altieri 2002).

An unexplored approach is to provide additional methodological or technical ingredients to existing cases that have reached a certain level of success. Clearly, in each country there are restraining factors such as lack of markets, and lack of appropriate agricultural policies and technologies which limit scaling up. On the other hand, opportunities for scaling up exist, including the systematization and application of approaches that have met with success at local levels, and the removal of constraining factors. Thus scaling up strategies must capitalize on mechanisms conducive to the spread of knowledge and techniques, such as:

- Strengthening of producers' organizations through alternative marketing channels.
- Develop methods for rescuing/ collecting/evaluating promising agreocological technologies generated by experimenting farmers and making them known to other farmers for wide adoption in various areas

- Training government research and extension agencies on agroecology in order for these organizations to include agroecological principles in their extension programs.
- Develop working linkages between NGOs, government organizations and farmers organizations for the dissemination of successful agroecological production systems emphasizing biodiversity management and rational use of natural resources.

From a worldwide survey of sustainable agriculture initiatives analysts concluded that if sustainable agriculture is to spread to larger numbers of farmers and communities, then future attention needs to be focused on:

- Ensuring the policy environment is enabling rather than disabling
- Investing in infrastructure for markets, transport and communications;
- Ensuring the support of government agencies, in particular, for local sustainable agricultural initiatives;
- Developing social capital within rural communities and between external agencies.

The main expectation of a scaling-up process is that it should expand the geographical coverage of participating institutions and their target agroecological projects while allowing an evaluation of the impact of the strategies employed. A key research goal should be that the methodology used will allow for a comparative analysis of the experiences learned, extracting principles that can be applied in the scaling-up of other existing local initiatives, thus illuminating other development processes.

Outlook and Prospects

There is no question that small farmers located in marginal environments in the developing world can produce much of their needed food. The evidence is conclusive: new approaches and technologies spearheaded by farmers, NGOs and some local governments around the world are already making a sufficient contribution to food security at the household, national, and regional levels. A variety of agroecological and participatory approaches in many countries show very positive outcomes even under adverse conditions. Potentials include: raising cereal yields from 50 to 200%, increasing stability of production through diversification, improving diets and income, contributing to national food security and even to exports and conservation of the natural resource base and agrobiodiversity (Pretty *et al*., 2003).

Whether the potential and spread of these thousands of local agroecological innovations is realized depends on several factors and actions (Altieri, 2002). First, proposed NRM strategies have to deliberately target the poor, and not only aim at increasing production and conserving natural resources, but also create employment, provide access to local inputs and output markets. New strategies must focus on the facilitation of farmer learning to become experts on NRM and at capturing the opportunities in their diverse environments.

Second, researchers and rural development practitioners will need to translate general ecological principles and natural resource management concepts into practical advice directly relevant to the needs and circumstances of small-holders. The new pro-poor technological agenda must incorporate agroecological perspectives. A focus on resource conserving technologies that uses labor efficiently and on diversified farming systems based on natural ecosystem processes will be essential. This implies a clear understanding of the relationship between biodiversity and agroecosystem function and identifying management practices and designs that will enhance the right kind of biodiversity which in turn will contribute to the maintenance and productivity of agroecosystems.

Technological solutions will be location specific and information intensive rather than capital intensive. The many existing examples of traditional and NGO-led methods of natural resource management provide opportunities to explore the potential of combining local farmer knowledge and skills with those of external agents to develop and/or adapt appropriate farming techniques.

Third, major changes must be made in policies, institutions, and research and development to make sure that agroecological alternatives are adopted, made equitably and broadly accessible, and multiplied so that their full benefit for sustainable food security can be realized. Existing subsidies and policy incentives for conventional chemical approaches must be dismantled. Corporate control over the food system must also be challenged. The strengthening of local institutional capacity and widening access of farmers to support services that facilitate use of technologies will be critical Governments and international public organizations must encourage and support effective partnerships between NGOs, local universities, and farmer organizations in order to assist and empower poor farmers to achieve food security, income generation, and natural resource conservation.

There is also need to increase rural incomes through interventions other than enhancing yields, such as complementary marketing and processing activities. Therefore traditional skills and knowledge provides a launching pad for additional learning and organizing, thus improving prospects for community empowerment and self-reliant development.

Equitable market opportunities should also be developed, emphasizing fair trade and other mechanisms that link farmers and consumers more directly. The ultimate challenge is to increase investment and research in agroecology and scale up projects that have already proven successful to thousands of other farmers. This will generate a meaningful impact on the income, food security, and environmental well-being of the world's population, especially of the millions of poor farmers yet untouched by modern agricultural technology.

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