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Cover photo: Soil and Water Conservation Park in Anji County,
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Soil and land resources for agricultural production: General trends and future scenarios - A worldwide perspective

Winfried E. H. Blum

Abstract

Based on the global distribution of land and soil quality and the world population, future trends in the agricultural use of land and soil resources are described, which will severely compromise future global food and fiber production through the increase and the spatial changes of world population, through the loss of fertile land caused by insufficient soil management and through urbanisation and industrialization. Moreover, future changes in life style and the increasing demand for food and bioenergy, through changes in world economy, through climate change and a worldwide decrease in fresh water supply, sustainable land use for the production of food and fiber will be under threat.

Until 2050 global food production must be doubled for satisfying global needs. Our scenarios should help to preview future changes, to counterbalance and to mitigate possible negative impacts, thus sustaining global food security.

Key Words: Global distribution of land and soil quality, Future trends in the use of land resources, Food and fiber production, Food security

1 Introduction

Fig. 1 depicts the goods and services provided by land and soil. These goods and services are based on the capacity of land and soil to perform specific functions, each of which are important for human wellbeing and the environment (Blum, 2005):

1. Production of biomass through agriculture and forestry;
2. Protection of the ground water and the food chain against contamination, and maintaining biodiversity by filtering, buffering and transformation activities;
3. Preservation of the gene reserve, which is by far the largest of the globe, and 3 – 4 times larger within the soil than that above ground, thus, providing a very significant habitat;
4. Provision of the physical basis for infrastructural development, such as housing, industrial production, transport, dumping of refuse, sports, recreation and others;
5. Serve as a source of raw materials, furnishing gravel, sand, clay and other materials (e.g., for infrastructural development);
6. Preservation of the geogenic and cultural heritage by concealing and protecting archaeological and palaeontological remains.
In the context of agricultural land use, the function to produce biomass is the most relevant to sustain food production and respond to cultural practices conducive to sustainable agricultural land management. Therefore, in the following section we will discuss food security from the perspective of sustainable production see also Blum and Nortcliff (2013).

We will focus on environmental opportunities and threats, especially those concerning natural resources, such as land surface, topography and soils. The aspects of water and climatic conditions will be included.

2 Global food and soil resources

Blum and Eswaran (2004) presented data illustrating the global distribution of soil and land resources [the principal categories being the Soil Orders of Soil Taxonomy (Soil Survey Staff, 1999)] and corresponding populations. The population data have been adjusted to reflect the 2010 estimate of global population (6.9 billion). Table 1 presents the land area occupied by each soil order or land class and an estimate of the number of people living on each. Ultisols, Alfisols, Inceptisols and Entisols have high populations, together supporting over 70% of the global population. Most of these soils present favourable conditions for agriculture but represent only 44% of the land area.

In temperate parts of the world, Alfisols and Mollisols have high concentrations of people. The Mollisols occupy about 6.4% of the land surface and have about 6.6% of the global population. These two soil orders are some of the most productive soils of the world, but are mostly found in temperate regions. In the tropics, a high proportion of the population is associated with river terraces (Entisols and Inceptisols) and Ultisols. However, Ultisols and Oxisols still present major problems for sustained low-input agricultural production.

The Gelisols of the Boreal zone have the lowest population density of approximately 2 persons per km$^2$, whilst the Andisols (developed on volcanic pyroclastic materials) have the highest with more than 129 persons per km$^2$. Some of the highest population densities in the world are on Andisols in Central Africa (Rwanda, Burundi and parts of western Zaire). The Ultisols and Vertisols, which are extensively used for agricultural production in the tropics, have population densities in excess of 100 and 120 persons per km$^2$ respectively. Fragile systems such as those with Histosols and Aridisols have densities of 21 and 24 persons per km$^2$ respectively and although these are low in comparison to other soil orders, these densities are in many regions threatening the sustainability of the systems.

Land quality is a measure of the ability of land to perform specific functions (see also Mueller et al., 2010). Beinroth et al. (2001) produced a 9-class land classification based on grain production.
<table>
<thead>
<tr>
<th>Soil and land quality classes</th>
<th>Land</th>
<th>2010 Population</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area ( \times 10^6 \text{ km}^2 )</td>
<td>%</td>
</tr>
<tr>
<td>1. Total ice-free land/population</td>
<td>128.57</td>
<td>100</td>
</tr>
<tr>
<td>2. Kinds of soils</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alfisols</td>
<td>11.52</td>
<td>8.96</td>
</tr>
<tr>
<td>Andisols</td>
<td>0.84</td>
<td>0.65</td>
</tr>
<tr>
<td>Aridisols</td>
<td>14.34</td>
<td>11.15</td>
</tr>
<tr>
<td>Entisols</td>
<td>19.30</td>
<td>15.01</td>
</tr>
<tr>
<td>Gelisols</td>
<td>10.29</td>
<td>8.00</td>
</tr>
<tr>
<td>Histosols</td>
<td>1.40</td>
<td>1.09</td>
</tr>
<tr>
<td>Inceptisols</td>
<td>11.73</td>
<td>9.13</td>
</tr>
<tr>
<td>Mollisols</td>
<td>8.23</td>
<td>6.40</td>
</tr>
<tr>
<td>Oxisols</td>
<td>8.96</td>
<td>6.97</td>
</tr>
<tr>
<td>Spodosols</td>
<td>3.06</td>
<td>2.38</td>
</tr>
<tr>
<td>Ultisols</td>
<td>10.08</td>
<td>7.84</td>
</tr>
<tr>
<td>Vertisols</td>
<td>2.89</td>
<td>2.25</td>
</tr>
<tr>
<td>Shifting sands</td>
<td>4.86</td>
<td>3.78</td>
</tr>
<tr>
<td>Rocky land</td>
<td>11.93</td>
<td>9.28</td>
</tr>
<tr>
<td>Glaciers, water bodies</td>
<td>9.14</td>
<td>7.11</td>
</tr>
</tbody>
</table>

The respective areas of the globe occupied by these classes and the population associated with the classes are presented in Table 2. Class I lands which have ideal soils occurring in ideal climates for crop production and are characterised by high productivity, high response to management and minimal limitations occupy only 2.38% of the global land surface, but contribute over 40% of global food production. The 9.53% of global land resources in Classes II and III have minor limitations that are easily corrected and do not pose permanent restrictions to the use of land. Most of these lands are in the temperate regions of the world where the climate is moderate, with rare extremes of rainfall or temperature.

### Table 2  Land area (million km²) in land quality classes with estimated population (millions) in each class

<table>
<thead>
<tr>
<th>Land quality class</th>
<th>Area ( \text{million km}^2 )</th>
<th>Population ( \text{millions} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>3.06</td>
<td>405</td>
</tr>
<tr>
<td>II</td>
<td>6.40</td>
<td>949</td>
</tr>
<tr>
<td>III</td>
<td>5.85</td>
<td>320</td>
</tr>
<tr>
<td>IV</td>
<td>5.08</td>
<td>787</td>
</tr>
<tr>
<td>V</td>
<td>21.23</td>
<td>1,985</td>
</tr>
<tr>
<td>VI</td>
<td>17.13</td>
<td>812</td>
</tr>
<tr>
<td>VII</td>
<td>11.58</td>
<td>768</td>
</tr>
<tr>
<td>VIII</td>
<td>21.46</td>
<td>124</td>
</tr>
<tr>
<td>IX</td>
<td>36.78</td>
<td>751</td>
</tr>
</tbody>
</table>

Land Quality Classes IV, V and VI cover about 34% of the global land surface, largely in the tropics and support over 50% of the population. These soils and the environmental contexts in which they are found have a range of constraints from high ambient temperatures that reduce germination rates to low nutrient availability that limits biomass production of annual crops.

Class VII land occupying a little over 9% of the land surface includes shallow soils, those with high salt concentrations and those with high organic matter levels. Shallow soils are normally considered not suitable for agriculture, saline soils may be used with specific adaptive crops and cropping practices. Class VIII lands occupy almost...
17% of the land surface; they have low temperatures and/or steep slopes and are generally considered unsuitable for agriculture. Class IX lands occupy over 28 percent of the land surface and are comprised of soils with inadequate moisture to support annual crop production.

The worldwide distribution of these nine land quality classes is shown in Fig. 2. In Table 3, the percent of land area in the main biomes as a function of land quality (Blum & Eswaran, 2004), is shown, revealing that only about 35% of the highly productive soils (Classes I – III) occur in the tropics, whereas 65% occur in regions with boreal, temperate and Mediterranean types of climate, mostly in the northern hemisphere.

Inherent Land Quality Assessment

Based on Buringh (1985), FAO (1995) and our own calculations, about 12% of the world land surfaces are suitable for food and fibre production, 24% can be used for grazing, 31% produce forests and 33% are unsuitable for any kind of sustainable use, mainly because of climatic constraints.

Summarizing, it can be stated that food security depends essentially on the 12% of the land surface with soil quality Classes I – III, where about 25% of the world population lives and all traded food and fibre for the world market is produced.

**Table 3** Percent of land area in major biomes as a function of land quality

<table>
<thead>
<tr>
<th>Biomes</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tundra</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15.62</td>
<td></td>
</tr>
<tr>
<td>Boreal</td>
<td>2.03</td>
<td>0.67</td>
<td>0.50</td>
<td>3.05</td>
<td>2.63</td>
<td>1.08</td>
<td>0.09</td>
<td>10.02</td>
</tr>
<tr>
<td>Temperate</td>
<td>2.14</td>
<td>2.55</td>
<td>0.70</td>
<td>1.31</td>
<td>4.76</td>
<td>1.66</td>
<td>2.01</td>
<td>15.29</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>0.30</td>
<td>0.15</td>
<td>1.35</td>
<td>0.08</td>
<td>0.65</td>
<td>0.03</td>
<td>2.56</td>
<td></td>
</tr>
<tr>
<td>Desert</td>
<td></td>
<td></td>
<td></td>
<td>1.42</td>
<td></td>
<td></td>
<td></td>
<td>29.61</td>
</tr>
<tr>
<td>Tropical</td>
<td>0.25</td>
<td>2.43</td>
<td>1.51</td>
<td>1.83</td>
<td>9.90</td>
<td>8.53</td>
<td>2.31</td>
<td>26.90</td>
</tr>
<tr>
<td>Total</td>
<td>2.38</td>
<td>4.98</td>
<td>4.55</td>
<td>3.95</td>
<td>16.51</td>
<td>13.32</td>
<td>9.01</td>
<td>28.61</td>
</tr>
</tbody>
</table>

3 Threats to land and soil compromising food production

There is concern that the natural functions of soils are increasingly threatened by changes in the environmental context (Scheffer et al., 2001). These changes are frequently human induced or human influenced (Foley et al., 2005). Agricultural activities have a clear impact on global environmental change (Tilman et al., 2001). A number of the recent national and international approaches to soil protection have highlighted a list of possible threats to the soil’s capacity to perform its functions. For example, in presenting the case for a European Soil Protection Strategy the Commission of the European Communities (2002) outlined a series of threats to the sustainable use of soil: a) soil sealing, b) erosion, c) decline in organic matter, d) contamination, e) loss of biodiversity, f) compaction, g) salinisation, and h) flooding and landslides. Some of these threats related to human activities are summarised in Fig. 3.

Fig. 3 The impact of human activities on soil (from Blum, W. E. H., Threats to Soil Quality in Europe, pp. 5–10, JRC Scientific and Technical Reports EUR 23438 EN, Ispra, Italy, 2008)

3.1 Impact of human activities on soil

Most of the threats to land and soil arise because we expect the soil to perform a range of functions, in some cases many functions at the same. By steadily increasing the demands on the soil from these functions we have often created an unstable system where the soil becomes less resilient and more vulnerable (Lal, 2009; Lal, 2007; Pretty, 2008). These threats are increasingly seen as particularly relevant to the biomass production function of soils, and hence impact global food security.

3.1.1 Soil sealing through urbanisation and industrialisation

Establishment of the infrastructure for modern life, housing, roads or other land developments is known as soil sealing. When land is sealed, the soil is unable to perform many of its functions including the absorption of rainwater for infiltration, and filtering in general. In addition sealed areas may have a great impact on surrounding soils by changing water flow patterns. Soil sealing is almost irreversible and there is increasing concern amongst governments and environmental regulators at this permanent loss of soil and the associated loss of ecosystem functions.

A novel manner in which the extent of soil sealing may be viewed is by examining the view of the Earth from space at night with the lights associated with urban development visible. Fig. 4 shows a recent example of the night time view of the Earth. Whilst not an exact correspondence it is also clear that much of the higher quality land is also associated with the areas of highest levels of urbanisation (compare also Foley et al., 2005). There is clear
evidence of high levels of urbanisation in North America, Western Europe and Japan (The Earth Institute, 2005), areas frequently strongly associated with good quality land (see Classes I – III in Fig. 2). But this image also highlights some recent changes such as the increasing urbanisation in the Indian sub-continent and China. Any further extension of urban growth will occur on best soils because our ancestors had chosen those soils for their first settlements. An estimation of current daily losses of soil through urbanisation, industrialisation and transport in the European Union (total surface 4,324,782 km²) amounts to about 1,200 ha per day, corresponding to 12 km². A very rough estimation of daily soil losses at the global scale amounts to about 25,000 – 30,000 ha per day, corresponding to 250 – 300 km².

3.1.2 Erosion

While erosion is a natural process some activities of humankind may result in a dramatic increase in erosion rates, especially unsustainable agricultural land use (Lal, 2001). As soil is an essentially non-renewable resource, when erosion is serious it is generally irreversible and the soil is lost forever.

Lal (2003; 2005) also highlighted the close link between the preferential erosional loss of organically enriched topsoil and the impact this may have on the global carbon budget. Whilst the loss of the soil and the associated soil carbon loss are major concerns, frequently there are additional environmental impacts because the soil is transported to watercourses adding contaminants and increasing the turbidity of the water, and its deposition downstream may cause further environmental damage, Boardman and Poesen (2006).

3.1.3 Decline in soil organic matter

Organic matter plays a central role in maintaining many key soil functions and is a major determinant of a soil’s resistance to erosion and underlying soil fertility (Lal, 2002). There is evidence that with a shift in the last half century towards greater specialisation and cereal monoculture particularly in temperate regions, losses of soil organic matter through decomposition are often not completely replaced. Specialisation in farming has led to the separation of livestock from arable production so that rotational practices which were important in the past in maintaining soil organic matter content no longer exist.

Losses of soil organic matter can be reversed with the adoption of land management practices such as conservation tillage, including no tillage cropping techniques, organic farming, permanent grassland, cover crops, mulching and manuring with green legumes, farmyard manure and compost.

Moreover, carbon as a major component of soil organic matter plays a major role in the global carbon cycle. Recent studies (for example Post & Kwon, 2000; Guo & Gifford, 2002) have emphasised the important role of the soil carbon pool in the context of global carbon fluxes.

3.1.4 Soil contamination

The introduction of contaminants in the soil may result in damage to or loss of individual or several functions of soils and the possible contamination of water. The occurrence of contaminants in soils above certain levels entails multiple negative consequences for the food chain and thus for human health, and for all types of ecosystems and other natural resources. A distinction is often made between soil contamination originating from clearly confined sources (local or point source contamination) and that caused by diffuse sources.

Fig. 4 illustrates the contamination which may occur through the excessive use of fossil energy and raw materials taken from inert positions in the inner part of the globe and deposited on the land surface through the atmosphere pathway, the water pathway and through terrestrial transport (e.g. in the case of plant protection products, fertilisers, biosolids, composts and other materials). Soil contamination may impact food production because the contaminants inhibit growth and the food may be unfit for human consumption. The increased urbanisation has the potential to produce soil contamination and further impact on global food production (Blum, 1998).

3.1.5 Decline in soil biodiversity

The soil is the habitat for a huge variety of living organisms (Bardgett et al., 2005; Gardi & Jefferey, 2009). Our knowledge of the larger organisms found in the soil system is incomplete. We have some knowledge of the rela-
Fig. 4 Soil contamination through excessive use of fossil energy and raw materials
(from Blum, W. E. H., Problems of Soil Conservation, nature and environment series no. 39, Council of Europe, Strasbourg, France, 1988)

ative magnitude but very sparse knowledge of the nature and function of microorganisms (see for example Pimentel et al., 2006). Soil bacteria, archeae, fungi, protozoa and other microorganisms play an essential role in maintaining the physical and biochemical properties needed for soil fertility (Barrios, 2007; Brussard et al., 2007). Larger organisms such as worms, snails and small arthropods contribute to reducing the size of organic matter which is further degraded by microorganisms, and carry it to deeper layers of soil, where it is more stable. Furthermore, soil organisms themselves serve as reservoirs of nutrients, suppress external pathogens and break down pollutants into simpler, often less harmful, components (Decaëns et al., 2006; Turbé et al., 2010). The interrelationships and interdependence amongst species are complex. The loss of a single species may have a cascading effect because of this interdependence (Pimentel et al., 2006).

Reductions in soil biodiversity make soils more vulnerable to other degradation processes and frequently reduce their ability to perform many ecosystem functions (Hunt & Wall, 2002; Matson et al., 1997). Because soil biodiversity interacts with many soil and broader environmental functions it is often used as an overall indicator of the state of soil health (see for example Harris & Bezdicek, 1994; Chapin et al., 2000).

3.1.6 Soil compaction

Soil compaction occurs on agricultural land when soil is subject to mechanical pressure through the use of heavy machinery or overgrazing, especially in wet soil conditions (Horn & Peth, 2011). Compaction reduces the pore space between soil particles and the soil partially or fully loses its capacity to absorb water. Compaction of deeper soil layers is very difficult to reverse (Horn et al., 2000). The overall deterioration in soil structure caused by compaction restricts root growth, water storage capacity, biological activity and stability and significant reduces fertility and food production (Horn et al., 2006; Clarke et al., 2008). Moreover, when heavy rainfall occurs, water can no longer easily infiltrate the soil, which may generate conditions conducive to soil erosion and even floods.

3.1.7 Salinization

Salinization is the accumulation in soils of soluble salts of principally sodium, magnesium, and calcium to the
extent that crop production is severely reduced. This process is often associated with insufficient irrigation practices as irrigation water will contain variable amounts of salts, in particular in regions where low rainfall, high evapotranspiration rates or soil textural characteristics impede the washing out of the salts which subsequently build-up in the soil surface layers (Singh, 2009). Irrigation with high salt content waters dramatically worsens the problem. In coastal areas salinization can also be associated with groundwater overexploitation leading to a lower water table and triggering the intrusion of saline marine water.

### 3.1.8 Floods and landslides

Floods and landslides are mainly natural hazards intimately related to soil and land management practices although their impact is often exacerbated by unusual environmental conditions. Landslides have a predominantly local impact on food production although they may temporarily impact food distribution through the disruption of communication networks. Floods may be both local, impacting a few hectares, or in extreme cases nationwide impacting thousands of km$^2$. Flooding may cause soil erosion with the loss of soil, seed and in extreme cases crops and pollution with sediments. Often in addition to the damage to soil and the natural environment there are also major impacts for human activities and human lives, damage to buildings and infrastructures, and loss of agricultural land.

### 3.1.9 Soil nutrient mining

Soil nutrient mining is possibly one of the most significant threats to food production in large parts of the tropics. Agricultural production in much of Africa is threatened by nutrient mining (Hartermink, 1997; De Jager et al., 2001). The context of agricultural production in much of the continent is one of fragile ecosystems, low inherent soil fertility and low use of modern inputs such as mineral fertiliser and improved crop varieties. The traditional practice in Africa and in particular Sub-Saharan Africa is one of fallow systems, where soil is left uncultivated to allow “recovery”. Increasing pressure on land through both rising population and in some countries exclusion of indigenous populations from parts of the landscape through land grabbing has resulted in a reduction in the length of fallow periods and in some cases their removal.

Nutrient balances which consider the inputs and outputs from the system have been used to estimate the magnitude and extent of nutrient mining. During the period of 2002–2004 85% of African agricultural land (1.85 million km$^2$) had annual nutrient mining rates of over 35 kg (N, P and K) per hectare, and 40% had annual rates greater than 60 kg per hectare. There are of course wide variation in the observed rates across the continent with an annual rate of 8 kg ha$^{-1}$ in Egypt and 88 kg ha$^{-1}$ in Somalia.

### 3.1.10 Desertification

Desertification is a complex process of land degradation through natural and human induced impacts (e.g. as a result of environmental responses to climate change), expressed in increased periods of droughts or overuse of natural resources, especially vegetation covers, by grazing or fuel wood collection, with subsequent soil degradation and losses, including salinisation (Anjum et al., 2010). Desertification increases the pressure on still productive land and soils for food production and may even cause social conflicts (Blum, 2009). Dregne (1998) estimated that 3.592 billion hectares of land had been affected by desertification. Eswaran et al. (2001) estimated that a “desertification tension zone” affects a total land area of about 4.23 billion ha, of which 1.17 billion ha occur in areas with high population density (<41 persons per km$^2$). Bai et al. (2008) estimated land degradation affected 3.5 billion ha or approximately 24% of the global land surface. Reynolds et al. (2007) discuss more sustainable approaches in the use of drylands at a global level in response to these pressures.

### 3.2 World population increase, migration and changes in food habits

World population increase amounts to about 80 million per year, with very unequal distribution at a worldwide level (IIASA, 2007; Lutz et al., 2008). About 70% occurs in Sub-Saharan Africa, South- and South-East Asia and South America.

Even with an increase in food production of more than 12% since 1990, the globally undernourished popula-
tion increased by about 9% (Barrett, 2010). Lal (2010) noted that the number of food insecure people rose from 854 million in 2007 to about 1020 million in 2009, also due to changes in market conditions and food pricing (see also FAO, 2008; IFPRI, 2008). According to FAOSTAT (2011), the number of people suffering hunger declined in 2010 to about 926 million. All these figures include only people who are protein/calorie malnourished and do not include those who are iron malnourished (about 2 billion), iodine malnourished (about 750 million) or show other specific nutritional deficiencies (World Health Organisation, 2000). D. Pimentel estimates that in total about 60% of the world population is malnourished (personal communication, based on FAO and WHO data).

In the second half of the 20th century, increases in food production of nearly 250% matched increases in population, from about 2.5 billion in 1950 to about 6.0 billion in 2000 (Blum & Eswaran, 2004; Godfray et al., 2010), mainly through the success of the “green revolution” (Borlaug, 2007). However, in the final years of the 20th century, population growth began to outstrip productivity increases. Therefore, the per capita food production showed a slight decrease over the time period. Moreover, in some areas (e.g. Africa), the green revolution had relatively little impact (Sanchez & Swaminathan, 2005), in part because of nutrient poor soils and limited access to fertilisers and insufficient agricultural tools (Scherr, 1999).

St. Clair and Lynch (2010) report that the global demand for food is expected to increase between 2.5-fold in the period 1990–2030. At the same time, the per capita area of land dedicated to food production, currently about 0.27 ha, continues to decrease because of population growth, which is exacerbated by increased urbanisation and soil degradation.

Lele (2010) noted that the main focus for poverty reduction is Africa and Asia, where 97% of the world’s food insecure are found (see also Rosegrant & Cline, 2003). Bai et al. (2008) note that the growth in cereal yields seen for much of the second half of the 20th century has slowed and that the climatic shifts predicted by IPCC may result in a 20%–40% drop in cereal yields, mostly in Africa and Asia. In addition, by 2050, there will be about 2.3 billion people more, which means that removing this poverty stress and feeding the additional population will require a 70% increase in cereal yields and a doubling or more of the output of developing countries. Even under an increase of more than 100% in grain production during the last 50 years, the land devoted to arable agriculture has increased by less than 10% (Godfray et al., 2010). It is likely that by 2050, we shall need 70%–100% more food to feed the estimated global population of 9 billion (Royal Society of London, 2009).

Besides the increase in world population, the migration of about 80–100 million per year from rural to urban areas (United Nations, 2004) is driving urbanisation and results in further sealing and degradation of productive land, as can be seen in many slum areas around urban centres in Africa, Asia and Latin America.

Moreover, the world-wide increasing demand for animal products, especially protein in the form of meat, but also eggs and milk (FAOSTAT, 2011; Godfray et al., 2010), is threatening food security by the consumption of grain in animal husbandry. For the production of one kg of chicken meat, about 2–3 kg of grain, for 1 kg of pork, about 4–6 kg of grain, and for 1 kg of beef, about 7–10 kg of grain are needed (Zhou et al., 2008). This means that large quantities of vegetable food are lost for human consumption, as they are used as animal feed without consideration of the additional environmental impacts (De Vries & de Boer, 2010; Xiong et al., 2008).

### 3.3 Climate change and shortage of fresh water resources

Climate change is threatening agricultural production in different ways; increased soil losses and degradation through increasing extreme weather events causing erosion by water and wind, floods and landslides, desertification and salinization (Alley et al., 2003; Haron & Dragovich, 2010), but also through an increasing lack of fresh water for irrigation and competition with water used in biofuel production (Bernardes, 2008), industry and households (Rosegrant & Cai, 2002). Schmidhuber and Tubiello (2007) discussed the complexity of climate change impact on food security at the global level (see also IPCC, 2007).

Moreover, food and biofuel production are exacerbating climate change through increasing deforestation for agricultural land use, urbanisation and industrialisation thus reducing carbon sequestration through soils. Through in-
tensive agricultural production of food and biofuels an increased output of greenhouse gases such as methane (CH$_4$) and nitrous oxide (N$_2$O) from soils and animals occurs, which have a much greater effect on climate change than CO$_2$.

The actual increase of water deficient regions, e.g. in the Near East, the Mediterranean and other world regions, is already playing a decisive role in food production through irrigation (IWMI, 2007).

On the other side, the increase in temperature, especially in the northern regions of America, Asia and Europe that have sufficient fresh water reserves, may partly compensate the losses of food production in water insecure areas and those with extreme soil losses and soil degradation.

3.4 Increasing demand for bioenergy: a competition for space, energy and water

Due to the steadily increasing prices for fossil energy in the form of oil and gas, the production of biofuel in gaseous form as biogas, in liquid form as biodiesel or ethanol, and in solid form such as straw and wood, has become economically interesting, especially in cases where financial subsidies are granted in view of the contribution to the mitigation of climate change by the use of biofuels. Goldemberg and Guardabassi (2009) discussed the advantages and disadvantages of biofuel products from carbohydrates (see also Demibras, 2007; OECD, 2007; Pimentel & Pimentel, 2007).

In many parts of the world, especially in Asia and Latin America, natural vegetation cover (e.g., forests) is destroyed in order to gain new surfaces for biofuel production (Fargione et al., 2008), mainly sugar cane growth and oil producing plants. The trilemma between food security, energy security and environmental security was highlighted by Popp (2010).

In view of the constantly decreasing surface for food production, due to urbanisation and industrialisation and soil losses and degradation through erosion and other forms, biofuel production is in strong competition with food production and therefore with food security, at least in the medium to long run (Pimentel et al., 2009; Tilman et al., 2009). Moreover, there are clear indications that agricultural biofuel production is endangering soil quality, because of the complete removal of organic matter and the return to the soil of insufficient organic matter residues for maintaining the organic matter status of soils and biodiversity (Blum et al., 2010; Cruse et al., 2010; Lal & Stewart, 2010).

Further competition exists for water. In many regions of the globe (e.g. in the Mediterranean Basin) water for food protection is already insufficient (Bernades, 2008).

According to P. Lamy, Dir. Gen. WTO (oral communication), based on data from FAO/OECD, 13% of all grain and 35% of all sugar cane sugar were used in 2011 for ethanol production and 16% of all vegetable oil for biodiesel at the world wide level, with increasing tendency.

3.5 World economy and emerging economic trends in food production and marketing

In the year 2008, during the world economic crisis, new economic concepts in food production and marketing emerged or were increasingly realized (Pieise & Thirtle, 2009). Speculation on the food market, e.g. through hedging (García & Leuthold, 2004; Williams, 2001) and the use of derivates became an important issue. Land grabbing (i.e. the purchase or rent of large territories, especially in countries in development) for food or biofuel production also increased considerably. For food supplies only more than 3 million ha land in Africa, Asia and Latin America were grabbed in the years 2006–2009 (von Braun & Meinzen-Dick, 2009).

Whereas hedging and the use of derivates allows for economic speculation with agricultural products, land grabbing can totally change the agricultural and rural landscapes of countries, as described by Adesina (2010) for Africa. Moreover, direct problems with soil fertility are to be expected, especially when food and biofuel production is maximized, in order to make a maximum profit out of the purchased or rented areas (Robertson & Pinstrup-Andersen, 2010). Land grabbing is a clear sign that many industrialized countries and international enterprises have recognized that land cannot be increased and due to constant losses of productive land in their own environ-
ment and increasing demands for food and energy at the local and global level, secured land in foreign countries and regions for sustaining food and biofuel production has become an important asset.

4 Summary and conclusions

The sustainable production (availability) of food is increasingly threatened through impacts deriving from human activities, especially changing forms of land use at local and global scales. Most critical are soil losses through sealing by urbanisation, industrialisation and transport, probably the most important threat to food security of all, but also erosion by water and wind and further severe forms of soil degradation, such as loss of organic matter, contamination, loss of soil biodiversity, compaction, salinisation, flooding, nutrient mining and desertification.

Moreover, the decrease in productive agricultural area and the degradation of the remaining productive surfaces is not the only threat to food security. There is an annual increase in the world population of about 80 million and a migration of about 80 – 100 million per year from rural into urban areas, where people depend on food markets without being able to produce their own food.

Moreover, climate change is threatening food security directly through increasing losses and degradation of soil, mainly through extreme events and in many regions a decrease of water resources is threatening rain-fed and irrigation agriculture. Meanwhile, an emerging severe competition occurs through the competition for space, energy and water for biofuel production and the concomitantly increasing demand for food and fibre on the local and world food markets.

New economic concepts and speculation on food markets can hamper the access to food through high fluctuation in prices. Moreover, the decreasing availability of productive agricultural land has led to land grabbing, mostly in developing countries of Africa, Asia and Latin America, threatening land and soil quality.

Without new approaches in land and water conservation at local and worldwide levels, it has to be expected that within one or two decades food shortage will severely further threaten millions of people and increase hunger, especially in countries in development.

References


Comparison of erosion and erosion control works in Macedonia, Serbia and Bulgaria

Ivan Blinkov¹, Stanimir Kostadinov², and Ivan Ts. Marinov³

Abstract

While soils are as essential to human society as air and water, soil degradation has not received nearly as much attention as the threats to these other elements. On the map of water erosion of Europe, Southern Europe is red “colored”. Erosion in the Balkan countries, through both on and offsite effects is a major cause of soil and water degradation.

This paper compares erosion control works in several countries from the Balkan region (Macedonia, Serbia, and Bulgaria). The basis for comparative analyses was various country reports as well as available published papers. Quantitative method-text analyze method was used for these study.

Natural conditions in the Balkan countries contribute to the appearance of various erosion forms and the intensity of the erosion processes. Over the history of these countries, people who settled this region used the available natural resources to fill their needs (tree cutting, incorrect plugging, overgrazing), which contributed to soil erosion. Organized erosion control works in the Balkans started in the beginning of the 20th century (1905 in Bulgaria). The highest intensity of erosion control works were carried out during the period 1945 – 1990. Various erosion control works were launched. Bulgaria had a large anti-erosion afforestation, almost 1 million ha. Bulgaria’s ecological river restoration approach has been in use for almost 50 years. Serbia contributed significant erosion and torrent control works on hilly agricultural areas. Specific screen barrages and afforestation on extremely dry areas are characteristic in Macedonia. A common characteristic for all countries is a high decrease in erosion control works in the last 20 years.

Key Words: Erosion, Erosion control works, Balkan

1 Introduction

Soil erosion is a natural process, occurring over geological time. Most concerns about erosion are related to accelerated erosion, where the natural rate has been significantly increased by human action (Fig. 1). Slope sediment transport processes are of two very broad types, first the weathering and second the transport of the regolith. Within each of these types, there are a number of separate processes, which may be classified by their particular mechanisms into groups, although many of these processes occur in combination. Soil erosion is regarded as the major and most widespread form of soil degradation, and as such, poses severe limitations to sustainable agricultural land use. Soil can be eroded away by wind and water. High winds can blow away loose soils from flat or hilly terrain. Erosion...
by water occurs due to the energy of water as it falls to earth and flows over the surface. Most slope processes are greatly assisted by the presence of water, which helps chemical reactions, makes masses slide more easily, carries debris as it flows and supports the growth of plants and animals. For both weathering and transport, the processes can conveniently be distinguished as chemical, physical and biological (Gobin et al., 2002). Erosion damages are classified in 2 basic groups:

(1) “on-site” damages (loss of topsoil and nutrients, disturbance of the hydrological regime, landscape changes) and

(2) “off-site” damages [flash (torrential) flooding, siltation of reservoirs and land in the downstream sections, soil halomorphism, chemical pollution of water with pesticides, fertilizers, and other pollutants connected to the suspended sediment that deposited in the downstream sections and reservoirs].

Fig. 1 Interconnectivity of the groups of factors active in degradation of watershed resources in a vicious circle (Özyuvac’ et al.)

Water erosion is the most widespread problem of land degradation in Europe. The European Council report produced through the GLASOD data method (Oldeman et al., 1991) enables an overview of land degradation processes in Europe. The South and Southeast region of Europe is significantly prone to water erosion. In parts of the region, erosion has reached a stage of irreversibility and in some places erosion has practically ceased because there is no soil left. With a very slow rate of soil formation, any soil loss of more than 1 t ha\(^{-1}\) yr\(^{-1}\) can be considered as irreversible within a time span of 50 – 100 years. Losses of 20 to 40 t ha\(^{-1}\) in individual storms, that may happen once every few years, are measured regularly in Europe with losses of more than 100 t ha\(^{-1}\) in extreme events (Morgan, 1992). It may take some time before the effects of such erosion become noticeable, especially in areas with the deepest and most fertile soils or on heavily fertilized land. However, this is all the more dangerous because, once the effects have become obvious, it is usually too late to do anything about it.

The erosion control concept depends on:

—status, role and importance of the object;
—natural (ecological) characteristics generally and partially;
—erosion intensity and erosion forms on the slopes and into the drainage network;
—state and functionality of existing biological alternatives (silvicultural and agro-meliorative) measures, hydraulic and other measures and activities;
—socio-economic characteristics of the area and region.

Erosion control concept depends on a scale of activity, could be understood as; single (on a small field) or on a watershed scale. A single concept is in use just to solve a single problem especially to minimize any single on-site effect (raindrop erosion, erosion from an agricultural parcel, erosion on construction sites etc.). On a scale of a watershed, erosion control is a part of a whole watershed management planning.

Erosion control measures are classified in the following groups: technical-ameliorative measures; biological-ameliorative measures (silvicultural and agro-meliorative); hydraulic structures; administrative measures and educative measures (Petkovic et al., 1999).

The purposes of technical ameliorative works are; reducing surface water runoff, storing water, reducing erosion on hills, enabling preconditions for biological works (afforestation and grassing as well as agricultural production) on steep slopes, rehabilitation of small gullies etc. In the group of technical-ameliorative works are contour ditches, contour walls (made by various materials), furrows and terraces (various dimensions, forms etc.), single and double wattles, fascines and gabions. These structures could be constructed of materials such as soil, stone, wood, and concrete. The choice of material, form, and dimension should be defined with detailed final designs. Usually in the areas where there is a large quantity of stone, stone structures or gabion structures are recommended. In other areas wood structures or wattles of fascines could be used. During the process of preparing a final design attention should be given to selection of species for planting (drilling), selection of planting (drilling) season, selection of appropriate techniques and approaches for planting (drilling), and selection of the method for land treatment and maintenance of the new plantation etc. Species that enable the fastest and best protection from erosion in the soil conditions of the location have an advantage in a process of selection. Domestic species should be selected in advance. Usually, nature shows the most appropriate species because the present species show their adjustment to various conditions. The characteristics of the species are very important. Species that tend to be in contact with the ground are recommended for steep slopes, especially on road slopes. Productive capacities of the species are secondary in the case of erosion control. In closed areas around reservoirs, the horticultural value of planted species is important. For silvicultural works in extreme locations, species should have wide ecological valence.

The selection of land treatment depends on the needed effects on the soil, water, and erosion. Maintenance of the plantations should be in accordance with their erosion control characters, the habitat conditions, as well as the current legislation. On rocky terrains setting turfs is a common measure employed.

All hydraulic construction: check dams, cascades, thresholds combined with longitudinal construction, dikes, and channels have multiple roles; reducing fluvial erosion and rehabilitation of previous damages, stream bank stabilization, improvement of the water regime, retention of large quantities of sediment for stabilization of landslides. On slopes where there are rock falls, appropriate retardation walls made by gabions or protective wire should be used.

2 Aims, objectives and methods

The main aim of this paper is to present specific erosion control measures and structures used in Macedonia, Bulgaria and Serbia as well as to show their effects.

The objectives of this study are:
— to present the current erosion intensity;
— to analyze and present a historical overview of erosion control in the different countries;
— to describe the most specific erosion control measures and structures in each country;
— to evaluate the effectiveness of the various erosion control measures.

Qualitative method-text analyze method was used in this study. The basis for the comparative analyses were
3 Study areas characteristics

The study area was located on the Balkan Peninsula. It encompasses the territory of Macedonia (MKD), Serbia (SR) and Bulgaria (BG).

All three groups of erosion factors – energy, resistance and protection (Morgan, 1992) promote soil erosion in the study area. The energy group includes the ability of rainfall and runoff to cause erosion. The relief in the southern part of Serbia is characterized by relatively steep slopes, which directly influences the energy of the erosive agents. About 80% of the territory of RM belongs to hilly and hilly-mountainous and mountainous regions where slopes are very steep. A significant part of Bulgaria also belongs to the mountain region (see Fig. 2).

Considering the resistance factors, the significant erodibility of the soil and geological substrata should be discussed. The geological structure of the major part of the area consists of rocks of high erodibility (conglomerates, schists, etc.) which contribute to the denudation process. Resistant rocks (granites, andezites, etc.) are present in a smaller area of this region.

The protection group of erosion factors is related to the population density and land use. The average population density in Serbia is moderate – about 100 inhabitants per km², 87 inhabitants per km² in Macedonia and 67 in Bulgaria. During its history, this region was permanently settled. Inadequate land treatment and intensive cutting of forests contributed to the high intensity of soil erosion. During the Ottoman Empire period, forest was proclaimed “res nullius”, meaning “nobody is the owner of the forest and everybody can cut for filling their own needs”. As a result, much of the region was converted from forest to bare land, which rapidly increased soil erosion and torrential flows.

Because of the natural resource and socioeconomic conditions, this region is highly vulnerable to erosion. According to the European Environment Agency (1995), Macedonia, together with Albania, Serbia and Bosnia is the so-called “red zone” of water erosion in Europe.

4 Results

4.1 Erosion intensity

The EPM (Erosion Potential Method) is the most comprehensive erosion risk assessment method (ERAM) for meeting watershed management needs. It is an empirical model that estimates the quantity and quality of eroded sediment. EPM gives solution to almost all tasks associated with ERAM, including the evaluations of that depend on scale, that depend on sector or that depend on erosion types (Blinkov and Kostadinov, 2010). For the Balkan territory, the EPM method is the most appropriate for the hilly-mountain and mountain regions (Macedonia, Serbia, Bosnia, Montenegro) (Blinkov & Kostadinov, 2010).

Blinkov and Kostadinov (2010) also found that the use of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) for agricultural areas in the Balkans (hilly and valley) was limited because of the absence of data.
However, various methodologies are used for erosion mapping. While in Macedonia and Serbia the Erosion Potential Model by Gavrilović (1972) is in use, Bulgaria uses the USLE methodology. Data and maps between countries could be compared if data were converted from t ha\(^{-1}\) to m\(^3\) km\(^{-2}\).

### 4.1.1 Erosion intensity in Macedonia

According to the Erosion map of Macedonia (Gorgevic et al., WDI, 1993), 96% of the total area is affected by erosion. An area of 9,423 km\(^2\) or 36.65% of the total state area is in the highest categories (Ⅰ—Ⅲ). The total annual erosion production for Macedonia is about 17,000,000 m\(^3\) yr\(^{-1}\) or 680 m\(^3\) km\(^{-2}\) yr\(^{-1}\), with about 7,500,000 m\(^3\) yr\(^{-1}\) or 303 m\(^3\) km\(^{-2}\) yr\(^{-1}\) of sediment are moved away from the site where it is eroded. A significant part of these deposits within Macedonia, about 3,000,000 m\(^3\) yr\(^{-1}\) is not carried through the downstream sections of the rivers to the exit of the state territory, but are deposited in natural lakes and reservoirs.

For example, the rates of annual sediment yield to the biggest reservoirs in Macedonia are: Tikves (1,300,000 m\(^3\) yr\(^{-1}\) or 497 m\(^3\) km\(^{-2}\) yr\(^{-1}\) ), Kalimanci (420,000 m\(^3\) yr\(^{-1}\) or 970 m\(^3\) km\(^{-2}\) yr\(^{-1}\) ). Typical for these reservoirs is that a great part of the eroded material was deposited in the so called “useful storage of the reservoir”, decreasing water resources of the reservoir (Trendafilov et al., 2002).

### Table 1 Erosion distribution in Macedonia (by EPM methodology)

<table>
<thead>
<tr>
<th>Degradation category (erosion processess)</th>
<th>Area (km(^2))</th>
<th>Percent (%)</th>
<th>Erosion intensity (m(^3) km(^{-2}) yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>I extremely high</td>
<td>698</td>
<td>2.77</td>
<td>&gt;3,000</td>
</tr>
<tr>
<td>II high</td>
<td>1,832</td>
<td>7.38</td>
<td>1,500 – 3,000</td>
</tr>
<tr>
<td>III medium</td>
<td>6,893</td>
<td>27.78</td>
<td>1,000 – 1,500</td>
</tr>
<tr>
<td>IV low</td>
<td>7,936</td>
<td>31.98</td>
<td>500 – 1,000</td>
</tr>
<tr>
<td>V very low</td>
<td>7,463</td>
<td>30.09</td>
<td>70 – 500</td>
</tr>
<tr>
<td></td>
<td>25,713</td>
<td>100.00</td>
<td></td>
</tr>
</tbody>
</table>

### 4.1.2 Erosion intensity in Serbia

The erosion map for Serbia was made in 1975 using EPM methodology. This map shows that, of the total area of Serbia, 86% is endangered by soil erosion of various rates. For the province of Vojvodina 72% of the area is endangered by soil erosion, and for the province of Kosovo and Metohija, 95% of the area is endangered. The new map of erosion produced in 2001 was little different than the map of 1975. Total annual erosion production in Serbia is 37,000,000 m\(^3\) yr\(^{-1}\) or 422 m\(^3\) km\(^{-2}\) yr\(^{-1}\) (Serbia: 488 m\(^3\) km\(^{-2}\) yr\(^{-1}\), Kosovo and Metohija: 249 m\(^3\) km\(^{-2}\) yr\(^{-1}\) ); annual sediment yield is 9,000,000 m\(^3\) yr\(^{-1}\), or 106 m\(^3\) km\(^{-2}\) yr\(^{-1}\).

In the normal erosion, which is a positive process, erosion intensity goes up to 100 m\(^3\) km\(^{-2}\) yr\(^{-1}\).

The most endangered region in Serbia is the southeast part of the country that is close to the Macedonia and Bulgaria borders.

### 4.1.3 Erosion intensity in Bulgaria

Data about Bulgaria is slightly different. While in Macedonia and Serbia was used EPM (methodology by Gavrilovic) and values are expressed in m\(^3\) yr\(^{-1}\) or m\(^3\) km\(^{-2}\) yr\(^{-1}\), in Bulgaria is used USLE method for defining erosion intensity, i.e., erosion production (by EPM) or soil loss (by USLE) and values are expressed in t ha\(^{-1}\) yr\(^{-1}\). It was assessed, that for 30% of the territory of Bulgaria, the potential erosion risk exceeds 40 t ha\(^{-1}\) yr\(^{-1}\), and around 62% of the entire area, the risk is higher than 10 t ha\(^{-1}\) yr\(^{-1}\). The estimated “actual” average annual soil loss rates vary from 0.14 t ha\(^{-1}\) yr\(^{-1}\) on forest lands to 2.7 t ha\(^{-1}\) yr\(^{-1}\) on pastureland and from 4.8 t ha\(^{-1}\) yr\(^{-1}\) on cropland to 12.7 t ha\(^{-1}\) yr\(^{-1}\) on vineyards, and orchards, resulting in the net average annual soil loss volume, estimated of 32,000,000 t (290 m\(^3\) km\(^{-2}\) yr\(^{-1}\) ), as over 2/3 of which originates from cropland (Lazarov et al., 2002; Rousseva et al., 2003). According to the National Long-term Erosion Control Programme (NLECP) estimations, the average annual soil losses at end of 70\(^{th}\) of the last century were 136,000,000 t (Biolchev et al., 1977). It would take into ac-
count that 68% of which was formed on the croplands, which represent 34.6% of the agricultural lands of Bulgaria at this period. The last study shows that the territory of Bulgaria represents 2.5% of the EU 27 countries area and contributes with 3.8% of the total soil erosion losses, estimated for that countries (Rousseva, 2012).

For the forestry fund the whole classified area at the end of year 2004, according to the degree of erosion, was about 292,000 ha which is 7.2% from the whole forest area (Marinov & Bardarov, 2005). It was found that the most widely affected by erosion were territories of the Regional Forestry Boards (RFB) – Blagoevgrad, Kardjali, Kiustendil, Sofia and Smolian. These areas vary between 30,000 and 60,000 ha. The distribution, according to the area affected to a different degree by erosion, as a percentage of the whole forest area of the respective forestry boards shows that the RFB Blagoevgrad, Kardjali, Kiustendil and Smolian have the highest percentage of territory affected by erosion-from 12% to 17%.

The methodological approach used in Serbia and Macedonia was also applied in Bulgaria, in particularly for the estimation of the sediment transport from the river Rakovitsa (747.5 ha), representative tributary for the middle part of the Struma river. It was established that the average total sediment transport (suspended and bed-load) using Poliakov-Kostadinov’s method (Kostadinov, 1993) is 340 m$^3$ km$^{-2}$ yr$^{-1}$ (Marinov et al., 2005).

### 4.2 Erosion control

#### 4.2.1 Erosion control in Macedonia

Few studies (Blinkov & Trendafilov, 2004, 2005, 2007; Blinkov et al., 2007), report for impressive positive results in this aspect.

Measures to control erosion were initiated in the early 1900’s, aimed mostly at protecting rivers and reservoirs. Following passage of the Law on Financing Melioration Systems (1958), these measures were strengthened, and as of 1985, 285 torrents were regulated. The water management projections anticipate continuing this work.

Measures to control erosion on deforested barren lands have also been under way since 1945, when restrictions were placed on nomadic breeding of goats and sheep in forests. This measure, though unpopular, led to a recovery of degraded forest and shrub land.

There were few acts directly related to erosion control in the past; the Act for afforestation of bare land (1951), Act of erosion control on steep slopes (1952), and the Act of steep slopes protection and torrent control (1957). Later, these acts were suspended. As part of the erosion control programme an “Afforestation Fund” was established in 1970 and it existed until 1990.

Until 1990, erosion control measures and activities were on “higher level” and institutional support was higher. There were sections for erosion control in all regional water management enterprises. There were parts of the budget aimed at erosion control. Now, the situation is the opposite. Unfortunately, erosion is one the biggest environmental and economic problems in Macedonia, but there are no special funds available for erosion control.

In the period 1950’s – 1970’s, classical stone barrages were usually constructed. Then building of concrete barrages began. These structures were made by water management enterprises, where in past there existed a sector for erosion and torrent control. Now water management is in a transformation period. Plans are only partially completed. About 65% of planned hydraulic structures were built, but only 25% of planned afforestation occurred.

#### 4.2.2 Erosion control in Serbia

The organized erosion and torrent control works (ETCW) in the territory of Serbia started prior to 1900 but the organized work began in 1907. The first works were for torrent control and channel training at the zones of intersections with railways, aiming at railroad protection.

There were works in the torrents of the Grđelička Klisura gorge in the South-East of Serbia, where the international railway line and road Belgrade-Skopje-Athens passes.

During the period of almost 100 years in Serbia the technology mostly applied were Classical European, French and Prof. Rosić’s System of torrent control (Kostadinov, 2007).
In the field of erosion and torrent control in Serbia, especially after the Second World War (period 1946–1989) significant results have been achieved. Many roads and railways, settlements, industry, agricultural soil and storage reservoirs have been protected (fully or partially), from sedimentation and from torrent floods. Still, this is not enough, considering the present conditions and requirements. In the last 15 years there has been an intensification of erosion processes. For almost 100 years of ETCW in Serbia, it is characteristic that erosion control works were not performed on farmland on the slopes, except in the period 1955–1966 when there was a small effort to extend these works (Kostadinov, 2007).

4.2.3 Erosion control in Bulgaria

The erosion control activities on the territory of Bulgaria was started at the end of the 19th century (1895) when the first erosion control plantations have been established (Stara Zagora, Kniazhevo, Dupnitsa, Kiustendil). The organized erosion and torrent control works started in 1905 when the first Section (Bureau) of torrent stabilisation and afforestation was created.

A significant amount of erosion control activities have been performed on the forest’s territories and hydrographic network. A lot of studies (Kostov et al., 1995; Zakov & Marinov 2003; Rousseva et al., 2006; Panov, 2000; Zakov, 2005; NFB, 2005) report for impressive positive results in this aspect.

During the period 1905–1944 eroded lands, spread on the area of 170,000 ha have been afforested and 160,000 m³ stone barrages (check dams) and thresholds (< 2.0 m above torrent bed) have been constructed. A National Long-term Erosion Control Programme (NLECP) was designed and implemented since 1982 (Biolchev et al., 1977). The NLECP made provisions for design of erosion control measures at a level of catchment, administrative territorial unit or the area of the co-operative farm. About 450,000 m³ barrages and thresholds, 380,000 m³ small stone thresholds and 350,000 m³ wattles have been constructed during the period 1945–1989. This period is also remarkable for comprehensive afforestation of 1,900,000 ha of which 760,000 ha (about 40%) are anti-erosion forestation, and development of 20,000 ha shelterbelts (Zakov, 2005). In this period, the stabilisation of the torrents has been recognized as a substantial part of erosion control activities. More than 80 large complex erosion control projects have been designed and applied in the dam watersheds. The measures limited significantly the siltation of the dams. The coefficient of siltation, defined as a ratio between actual and predicted siltation, was low for nine of 15 dams studied and the deposition was within the range of acceptable values for two dams. There are many successful stabilised torrential beds by biological measures in this period. An example is the bed of the torrential Perperek River, in the vicinity of Kardzhali, where a system of forest belts has been established. It resulted in the retention of large amounts of sediments outside the dam Studen kladenets and provision of land suitable for forest and agricultural production.

The 1990s was characterized by a transition towards a market-oriented economy and land-property reform. Considering erosion control of the agricultural lands, the 1990’s are marked as a decade of the complete carelessness. Permanent constructions to control erosion, once completed, have not been maintained after that, so their disintegration has been in progress. Many terraces have been damaged, collection ditches have been broken, grassed land has not been protected from excessive grazing (Rouseva et al., 2006). During the period 1989–2004 about 16,000 ha eroded lands has been afforested, 10,000 m³ barrages and thresholds, 12,000 m³ small stone thresholds and 7,000 m² wattles has been constructed (NFB, 2005). Some decrease of the afforestation works has taken place in the 1990s and especially since 1995, when the mean annual erosion control afforestation rate has been below 600 ha yr⁻¹. The erosion control hydro-technical construction works rate have been also decreased significantly while barrages of a volume about 1,000 m³ yr⁻¹ have been built (Zakov, & Marinov, 2003).

4.3 Comparison of erosion intensity between countries

Values for erosion intensity for Bulgaria are lower than those of Macedonia and Serbia, this may be a result of the methodology used (Table 2). USLE methodology only predicts the amount of soil loss that results from sheet or rill erosion on a single slope and does not account for additional soil losses or erosion production that might occur.
from gully, wind even from weathering, landslides, landfalls.

<table>
<thead>
<tr>
<th>Country</th>
<th>Erosion intensity</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$m^3 \text{ yr}^{-1}$</td>
<td>$m^3 \text{ km}^{-2} \text{ yr}^{-1}$</td>
</tr>
<tr>
<td>Macedonia</td>
<td>17,000,000</td>
<td>680</td>
</tr>
<tr>
<td>Serbia</td>
<td>37,000,000</td>
<td>422</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>32,000,000</td>
<td>290</td>
</tr>
</tbody>
</table>

### 4.4 Comparison of erosion control works between countries

#### 4.4.1 Quantity of erosion control works

Bulgaria has focused significant attention on afforestation of bare and other erosive land, with 950,000 ha, Serbia and Macedonia follows with around 120,000 ha afforested area (Table 3).

<table>
<thead>
<tr>
<th>Country</th>
<th>Anti-erosion afforestation</th>
<th>Hydrological structures on the forest fund</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ha</td>
<td>m$^3$</td>
</tr>
<tr>
<td>Macedonia</td>
<td>120,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Serbia</td>
<td>120,987</td>
<td>1,501,656</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>950,000</td>
<td>617,000</td>
</tr>
</tbody>
</table>

Regarding the afforested (with new forests for erosion control) territory (8.6%) Bulgaria is one of the leaders in Europe. Macedonia paid significant attention to afforestation also. Percentage of afforested territory of the total country area is high also (4.67%).

On the other hand, Serbia paid more attention on building of hydraulic structures in the torrent beds. The quantity of 16.99 m$^3$ km$^{-2}$ for hydraulic structures is among the highest in Europe.

#### 4.4.2 Dynamics of erosion control works

A common characteristic for all three countries is that during the socialism period, there was a strong effort to control soil erosion. In the period after the fall of the old socialist system, erosion control efforts decreased rapidly.

Afforestation in Macedonia was most intensive in the period 1975–1985. According to Fig. 3, afforestation rapidly decreased from 1985 to 1995. In the latest 5 years, afforestation has increase and the average intensity of afforestation in last 5 years (2005–2010) was about 5,000 ha yr$^{-1}$.

There is no exact data available on hydraulic structures, but due to the collapse of and transformation of water management in the country, the trend of decrease continues.

For all three countries, the period from 1945–1990 was the “golden period” of erosion control works (see figures 3, 4, 5, 6, 7) when the intensity of implementing erosion control works are few times higher than in the other periods (before and after).
Fig. 4  Dynamic of erosion control works in Serbia

Fig. 5  Dynamic of erosion control activities in Bulgaria

Fig. 6  Comparison of dynamic of annual intensity of anti-erosion afforestation
4.5 Specific erosion control works

Various erosion control works are done in all countries, but there are some specific works that are common to a particular country that are not common in the other two countries.

4.5.1 Specific erosion control works in Macedonia

The most specific hydraulic structure in Macedonia are screw check dams- Herheulidze type (Fig. 8). These structures are built in the western part of Macedonia where confirmation type is Alpine type. Erosion intensity is very high, weathering is significant and it results in rock particles with huge dimension. This type of check-dams was built in a few torrents in the western part of Macedonia.

In the central part of Macedonia is a semiarid area where the total annual precipitation is less than 500 mm. The lowest measured annual precipitation in this area was 195 mm. This region is vulnerable to the desertification processes. Afforestation in this region was a challenge for various generations of experts. Various types of afforestation were carried out in this region using various tree species with aim to reduce erosion and greening of the area (see Fig. 9).

Fig. 7 Comparison of dynamic of annual intensity of building hydraulic structures

Fig. 8 Screw check-dam (barrage) type Herheulidze (torrent Arvati and torrent Pena)

Fig. 9 Afforestation in arid region in Macedonia (plantation in holes and in furrows)
4.5.2 Specific erosion control works in Serbia

Erosion control experts in Serbia used various types of check dams but the most specific are Rosic-type: Filtration check dams (Kostadinov, 1995). Presented on Fig. 10.

Serbia’s biological works, besides classical afforestation, includes plantations of orchards on erosive land in the hilly mountainous region.

While in Bulgaria and Macedonia the greatest part of erosive land is state owned, in Serbia a significant part of the erosive land is private property. Private owners’ interest is not only to protect land from erosion but to get an income from it. That was the main reason for orchard production on erosive land in the hilly mountain regions in Serbia (Kostadinov & Marković, 1996; see Fig. 11).

4.5.3 Specific erosion control works in Bulgaria

While the new trend in stream restoration in Europe is “ecological stream restoration”, it was carried out in Bulgaria long years ago. A typical example is the river Perperek where for the restoration only natural materials, wood and stone, were used. On Fig. 12 are presented photos from different periods (beginning of restoration and after a few decades). Now days this stream looks very natural. Bulgaria is one of the leaders in Europe in biological
works. In a region of Kardzhali a former “rocky desert” through intensive work was transformed into a good forest.

Another specific erosion control activities in Bulgaria are the using of the gabion thresholds which are built-up of separate horizontal parts of dry masonry stone encased in a metal net (Fig. 13). After the filled up of the thresholds and stabilized the sediments behind them, this terrain is forested.

![Fig. 13 Gabion thresholds](image)

5 Conclusions

Erosion intensity in Macedonia, Serbia and Bulgaria is among the highest in Europe, and erosion is assigned as one of the most important ecological and economic problems.

Faced with problems caused by soil erosion, organized erosion control began in the beginning of the 20th century.

The “golden period” of erosion control was the period of 1945-1990. After this period there has been a significant decrease of erosion control activities.

Serbia focused attention on building hydraulic structures. Intensity of $16.99 \text{ m}^3 \text{ km}^{-2}$ is among the highest in Europe. On the other hand, Bulgaria focused significant attention to anti-erosion afforestation – 950,000 ha and afforested 8.64% of the total area of the country, the highest in Europe.

Specific hydraulic structures are built in Macedonia – screw check-dams Herheulidze type. A specific practice for Macedonia is afforestation in extreme arid conditions.

Specific Rosic type check dams are characteristic in Serbia. Additionally, plantations of orchards on terraces in hilly mountain region are found in Serbia.

Beside mass afforestation, one of the most specific means of erosion control in Bulgaria is the “ecological river restoration” principle using natural materials: wood and stone. This has been a practice since about 1950. During the last few decades in Bulgaria for stabilizing of dry gullies the small gabion thresholds have been constructed.

References


ANNEX—Effects of anti-erosion afforestation

Serbia

Bulgaria
Effects of long-term organic material applications and green manure crop cultivation on soil organic carbon in rain fed area of Thailand

Tomohide Sugino¹, Wanida Nobuntou², Nuttapong Srisombut³, Praison Rujikun⁴, Suphakarn Luanmanee⁵, and Nongluck Punlai⁶

Abstract

A long-term field experiment on organic material application and crop rotation with green manure crops has been conducted since 1976 at Lopburi Agricultural Research and Development Center, Department of Agriculture, Lop Buri Province, Thailand, to clarify the effect of organic materials and green manure crops on soil organic carbon changes. The stock change factors that stand for the relative change of soil organic carbon on the carbon stock in a reference condition (native vegetation that is not degraded or improved). Stock change factor for input of organic matter ($F_I$), representing different levels of C input to soil such as organic material application, crop residue treatment and green manure crop cultivation, was computed with the present field experimental results. While the computed $F_I$ of “High input with manure” was within the range of IPCC default $F_I$ value, some of the computed $F_I$ of “High input without manure” was much higher than the IPCC default though it was varied due to the biomass production and nutrient contents of the green manure crops planted as the second crops after corn. Therefore, the $F_I$ computed by field experimental results can contribute to more accurate estimation of SOC changes in farm land especially in Southeast Asia because the default $F_I$ mostly depends on the experimental data in temperate zones. Moreover, the field experiment has focused the effect of reduced tillage practices on SOC changes and corn yield since 2011. The results of the experiment will be used to compute Stock change factor for management regime ($F_{mg}$) which represents the effects of tillage operations.

Key Words: Soil organic carbon, Organic material application, Green manure crop

1 Introduction

Green House Gas (GHG) emissions from the agricultural sector is 26 per cent of the total GHG emission in developing regions (UNFCCC, 2005). Farm lands stock an enormous amount of carbon as soil organic matters. Farm and forest lands can serve as carbon sinks if they are managed appropriately so as to increase or maintain soil carbon. The change of soil carbon is determined by the balance of carbon (e.g. manure) application and decomposition of organic matter in soil. It is greatly affected by the farm land management such as manure application, and by crop residue management and tillage.

IPCC (2006) has proposed three Tiers to develop an inventory of soil organic carbon (SOC) stock changes

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²Researcher, Department of Agriculture, Ministry of Agriculture and Cooperatives, Thailand
for mineral soils. In Tier 1, SOC changes can be estimated using the equation:

$$SOC = SOC_{REF} F_{LU} F_{MG} F_{I} A$$  \hspace{1cm} (1)$$

where SOC = soil organic carbon stock in the specific climate zone, soil type and management system, tons C; SOC\textsubscript{REF} = the reference carbon stock, t C ha\textsuperscript{-1}; F\textsubscript{LU} = stock change factor for land-use systems or sub-system for a particular land-use, dimensionless; F\textsubscript{MG} = stock change factor for management regime, dimensionless; F\textsubscript{I} = stock change factor for input of organic matter, dimensionless; A = land area, ha.

The stock change factors express the relative change of soil organic carbon on the carbon stock in a reference condition (native vegetation that is not degraded or improved). In Tier 1, the SOC stock is computed from the default reference SOC stocks (SOC\textsubscript{REF}) and default stock change factors (F\textsubscript{LU}, F\textsubscript{MG}, F\textsubscript{I}) proposed by IPCC. Tier 2 uses the same equation but country-specific information like stock change factors is incorporated. Tier 3 methods involve more detailed and country-specific models. Default stock change factors were computed using a global dataset of experimental results for tillage, input, set-aside, and land use. Most of the experiments were implemented in North America and Europe which are located in temperate zones and few are found in tropical zones especially in Southeast Asia (Fig. 1). Like other sources of GHG emissions in agriculture, decomposition / accumulation of soil organic matter is highly affected by environmental factors such as soil and climate. Therefore it is crucial to estimate the stock change factors using field experimental data in respective regions.

Long-term experiments are effective to evaluate the change in soil properties (Böhme et al., 2004; Parham et al., 2002). Since 1976, the Japan International Research Center for Agricultural Sciences (JIRCAS), and the Thailand Department of Agriculture (DOA), Ministry of Agriculture and Cooperative have conducted a long-term field experiment at the Lopburi Agricultural Research and Development Center, DOA, Lop Buri Province, Thailand. The experimental results of earlier studies involving the long-term effects of green manure, organic material and chemical fertilizer application on soil nutrient contents and yield of corn, as well as the effect of other factors like soil moisture on corn yield have been reported (Sangtong & Katoh, 2010; Fujimoto et al., 1996). In this report the stock change factors for input (F\textsubscript{I}) are estimated using field experimental data. The relevancy of the estimated factors is discussed by comparing them with the default factors of IPCC.

2 Research methodology

A field experiment was conducted to study the effect of long-term crop rotation with green manure crops and application of organic materials on SOC. The general properties of the soil in the experimental field are shown in Table 1. The soil is a Typic Paleustults, Ultisols in the USDA Taxonomy system. The treatments of plots are described in Table 2. Every year, corn was planted in May, the early rainfall period, and harvested in late August or early September. Mungbean (Vigna radiata) was used as the second crop after corn, and mimosa (Mimosa invisa), crotalaria (Crotalaria juncea) and ricebean (Vigna umbellate) were intercropped with corn from 1976 to 2005. Corn stalks were mulched between second crop planting except for Treatments 1 and 7 before 1980. After about 45 days of growth, crotalaria was cut and spread on the soil as mulch from 1980 to 1988. The residue of mimosa, crotalaria from 1989 - 2005 and ricebean was incorporated into the soil the following year. Velvet bean (Mucuna pruriens), soybean (Glycine max) and sunflower (Helianthus annuus) were planted as the second crops after 2006.

Fig. 1 Geographical distribution of field experiments cited for default stock change factors of IPCC

Source: By authors based on IPCC (IPCC, 2006).
Corn variety Suwan 1 was grown from 1980 to 1988, variety Nakhon sawan 1 was used from 1989 to 2005 and variety Nakhon sawan 2 was used after 2006. Chemical fertilizers of the conventional dosage were applied to Treatment 7–12 (Chemical fertilizer applied; CF). No chemical fertilizers were applied to treatment 1–6 (No/Low chemical fertilizer applied; NF) from 1976 to 2005 and the reduced dosage was applied after 2006. The application rate is shown in Table 2. Rice straw was mulched. City compost was incorporated and terminated in 1996. In 1990, every treatment except Treatment 6 and 12 (city compost plot) was limed with dolomite (0.5 t ha⁻¹) before planting corn.

The experimental design was a randomized complete block with three replications, and plot size was 5.25 m x 6.00 m. Corn was grown with a spacing of 75 cm x 25 cm. About a week before land preparation for planting corn, glyphosate and alachlor were applied to eradicate weeds. During cultivation, some pesticides such as azodrin were applied if any pest outbreaks were observed. The experiment was conducted under rainfed conditions.

SOC was determined by means of the Walkley-Black method (Walkely & Black, 1934). Since some of the original data in the early stage of the experiment was missing, most of the data were obtained as an average of the three replications. However, if the original data was available, data obtained were subjected to analysis of Duncan’s Multiple Range Test. For mean comparisons, significance was tested at $P < 0.05$.

### Table 1: General properties of the soil in the experimental field (as of 2010)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>% sand</th>
<th>% silt</th>
<th>% clay</th>
<th>Texture</th>
<th>pH</th>
<th>% OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–13</td>
<td>50.99</td>
<td>35.2</td>
<td>13.8</td>
<td>Loam</td>
<td>5.8</td>
<td>1.84</td>
</tr>
<tr>
<td>13–27</td>
<td>45.99</td>
<td>35.2</td>
<td>18.8</td>
<td>Loam</td>
<td>5.7</td>
<td>1.24</td>
</tr>
<tr>
<td>27–50</td>
<td>40.99</td>
<td>20.2</td>
<td>38.8</td>
<td>Clay loam</td>
<td>5.1</td>
<td>0.99</td>
</tr>
<tr>
<td>50–75</td>
<td>35.99</td>
<td>15.2</td>
<td>48.8</td>
<td>Clay</td>
<td>4.0</td>
<td>0.98</td>
</tr>
</tbody>
</table>

### Table 2: Treatments of plots

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>Control</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>Crotalaria</td>
<td>MZ-MG</td>
<td>L</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>Mimosa</td>
<td>MZ-F, stalk inc</td>
<td>L</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>Rice straw</td>
<td>MZ-MG, RS</td>
<td>O</td>
</tr>
<tr>
<td>5</td>
<td>11</td>
<td>Rice bean</td>
<td>MZ-MG, vinyl</td>
<td>O</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>Compost</td>
<td>MZ-F, Comp</td>
<td>O</td>
</tr>
</tbody>
</table>


L: Low input, M: Middle input, H: High input without manure, O: High input with manure; corresponding the input level proposed by IPCC (IPCC, 2006). See Table 4.

NF: No chemical fertilizer in 1976–2005 and N: P₂O₅:K₂O = 41.5 kg ha⁻¹–41.5 kg ha⁻¹–41.5 kg ha⁻¹ applied in 2006–2008.

CF: Chemical fertilizer applied (N: P₂O₅:K₂O = 100 kg ha⁻¹–100 kg ha⁻¹–50 kg ha⁻¹ in 1976–1979, 62.5–62.5–0 in 1980–1989, 62.5–62.5–62.5 in 1990–).
3 Results and discussions

SOC trends during the experiment are shown in Table 3. As of 2005, SOC increase in soils ranged from 1.31 to 1.97 times of the initial SOC in 1976 with the highest increase observed in Treatment 3 of NF followed by Treatment 6 and Treatment 12 of CF followed by Treatment 9. These treatments planted mimosa as a green manure crop or applied city compost. The SOC increase of Treatment 6 and 12 which applied city compost during 1976 to 1995 showed the highest SOC in 1995. SOC of these treatments reduced or marginally increased after the compost application was terminated in 1996. Even Treatment 1, which didn’t apply any fertilizers by 2005 but only incorporated crop residue of corn and mungbean after 1980, increased SOC significantly.

Values with the same letter (for 2008) in Treatments 1–6 and 7–12 respectively are not significantly different at $P<0.05$.

Values for 2008 are means followed by Standard Deviation.

$F_I$ (stock change factor for input of organic matter): Relative SOC changes of 2005/1976 to that of Treatment 1 (for Treatments 2–6) and Treatment 7 (for Treatments 8–12).

<table>
<thead>
<tr>
<th>Table 3</th>
<th>SOC trends (% in 0–15 cm depth) and computed $F_I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 NF Control</td>
<td>0.64</td>
</tr>
<tr>
<td>2 NF Crotalaria</td>
<td>0.64</td>
</tr>
<tr>
<td>3 NF Mimosa</td>
<td>0.64</td>
</tr>
<tr>
<td>4 NF Rice straw</td>
<td>0.64</td>
</tr>
<tr>
<td>5 NF Ricebean</td>
<td>0.64</td>
</tr>
<tr>
<td>6 NF Compost</td>
<td>0.64</td>
</tr>
<tr>
<td>7 CF Control</td>
<td>0.64</td>
</tr>
<tr>
<td>8 CF Crotalaria</td>
<td>0.64</td>
</tr>
<tr>
<td>9 CF Mimosa</td>
<td>0.64</td>
</tr>
<tr>
<td>10 CF Rice straw</td>
<td>0.64</td>
</tr>
<tr>
<td>11 CF Ricebean</td>
<td>0.64</td>
</tr>
<tr>
<td>12 CF Compost</td>
<td>0.64</td>
</tr>
</tbody>
</table>

An input factor ($F_I$) represents different levels of C input to soil. The default $F_I$ is proposed by IPCC as SOC changes in soil surface (0–30 cm) over 20 years in the respective management practices on crop land relative to nominal (“medium”) carbon input levels (IPCC, 2006). Table 3 shows $F_I$ computed with the present field experimental results during 1976 to 2005. For the treatments of NF (Treatments 1–6), Treatment 1 (NF control) was used as the nominal carbon input levels while Treatment 7 (CF control) was used as the nominal carbon input levels for the treatments of CF (Treatments 7–12).

The description of input level proposed by IPCC (IPCC, 2006) is shown in Table 4. According to the description, Treatments 2, 3, 5 of NF and Treatments 8, 9, 11 of CF belong to “High input without manure” except an initial stage (1976–1979) of the experiment, when all these treatments belong to “Low input”. Treatments 4, 6 of NF and 10, 12 of CF belong to “High input with manure” except Treatments 6 and 12 after 1996 when the compost application was terminated.
Table 4 The description of input level proposed by IPCC

<table>
<thead>
<tr>
<th>Input level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low residue return occurs when there is due to removal of residues (via collection or burning), frequent bare-fallowing, production of crops yielding low residues (e.g., vegetables, tobacco, cotton), no mineral fertilization or N-fixing crops.</td>
</tr>
<tr>
<td></td>
<td>Representative for annual cropping with cereals where all crop residues are returned to the field. If residues are removed then supplemental organic matter (e.g., manure) is added. Also requires mineral fertilization or N-fixing crop in rotation.</td>
</tr>
<tr>
<td>Middle</td>
<td>Represents significantly greater crop residue inputs over medium C input cropping systems due to additional practices, such as production of high residue yielding crops, use of green manures, cover crops, improved vegetated fallows, irrigation, frequent use of perennial grasses in annual crop rotations, but without manure applied (see row below).</td>
</tr>
<tr>
<td>High without manure</td>
<td>Represents significantly higher C input over medium C input cropping systems due to an additional practice of regular addition of animal manure.</td>
</tr>
<tr>
<td>High with manure</td>
<td></td>
</tr>
</tbody>
</table>

Source: IPCC (IPCC, 2006).

Comparing IPCC default $F_I$ (High input without manure: $1.11 \pm 10\%$, High input with manure: $1.44 \pm 14\%$ (IPCC, 2006), the computed $F_I$ was $1.13 - 1.49$ (Treatments 2, 3, 5; High input without manure) and $1.35 - 1.45$ (Treatments 4, 6; High input with manure) in NF, and $1.18 - 1.45$ (Treatments 8, 9, 11; High input without manure) and $1.37 - 1.48$ (Treatments 10, 12; High input with manure) in CF. While the computed $F_I$ of High input with manure was within the range of IPCC default value, some of the computed $F_I$ of High input without manure was much higher than the IPCC default. Due to the constraints of data availability, $F_I$ was computed by SOC data in soil surface (0–15 cm) in the present study while IPCC default $F_I$ is for 0–30 cm depth. The SOC change in surface soil is more active than subsoil (Yang & Wander, 1999). Therefore, the computed $F_I$ might be overestimated since the $F_I$ in subsoil (15–30 cm) could be lower than that of soil surface. All of the treatments implemented crop rotation with green manure crops namely, mungbean, mimosa, crotalaria and ricebean. There are a number of leguminous crops that can be used as green manure (McDonagh et al., 1993; Shahandeh et al., 2004; Torbert et al., 1996; Utomo et al., 1990) including the crops used in this experiment. However, the amount of biomass and nutrient components produced by the crops are widely varied. Table 5 shows the yield and nutrient content of selected green manure crops. Since mimosa provides a higher mass yield than traditional row crops (Huang et al., 2013), it will increase SOC more than the traditional row crops when it is used as a green manure crop. The carbon contents of organic matters by farmers are also varied resulting in a wide range of SOC changes according to the amount and raw material of manure applied.

It should also be noted that the amount of SOC increase or decrease is affected by the initial SOC. Some studies use SOC changes relative to initial SOC contents to avoid the influence of initial SOC values (Paul et al., 2002) when SOC change data with different initial SOC’s should be compared. As discussed above, the default stock change factors of IPCC are used to estimate the SOC stock at the specific time as multiplying the reference carbon stock by these factors. Reference carbon stock is a soil organic carbon stock under native vegetation and the default value proposed by IPCC is 47 t C ha$^{-1}$ in 0–30 cm depth (soils with low activity clay minerals, tropical moist) for the soil in the present experimental field (IPCC, 2006). The actual initial SOC in the present experimental field in 1976 was around 30 t C ha$^{-1}$ in 0–30 cm depth, which was much lower than the IPCC default carbon stock. The higher computed $F_I$ of “High input without manure” in some treatments than the IPCC default $F_I$ means that the effects of green manure crops for SOC changes were more obvious in the present experiment because of the lower initial SOC. On the other hand, the initial SOC was little affected by the SOC changes in “High input with manure” treatments. This suggests that since manure application has a quicker and greater effect on SOC changes than green manure crops which must decompose before increasing SOC, manure application might cover the impacts from the lower initial SOC.
In the Tier 2 of IPCC to develop an inventory of SOC, each country can use country-specific stock change factors. Table 6 shows the results of SOC change estimation (assumption: annual cropland in tropical moist region with low input levels and full tillage converted to high input with/without manure managements for 25 years) both by using IPCC default $F_I$ and computed $F_I$ in the present study. All the estimated SOC changes of “High input without manure” during 1980 – 2005 using the computed $F_I$ were greater than the estimated SOC changes using the default $F_I$. Though the actual SOC changes observed in the experimental field were still higher than the estimated SOC changes using the computed $F_I$, the use of $F_I$ computed by field experimental data can contribute to a more accurate estimation of SOC changes.

Since the present experiments mostly investigated the effects of green manure crops and organic material application, little information is available for the effect of tillage management on SOC, which can be used to compute $F_{MG}$. Therefore, a part of the field experimental treatments were modified in 2011 and a no-tillage practice was introduced to investigate long term effects of reduced tillage practices on SOC and corn yield. It is anticipated that the results of the on-going experiment will contribute to the improved $F_{MG}$ based on the field experimental data.

### Table 6 Estimated SOC changes in 0 – 30 cm depth by default $F_I$ and computed $F_I$ in the present study

<table>
<thead>
<tr>
<th>Treatment</th>
<th>$F_I$ (1 ha⁻¹)</th>
<th>SOCREF (0 t) (1 ha⁻¹)</th>
<th>SOC(0) (1 ha⁻¹)</th>
<th>SOC changes (SOC(0) – SOCREF) (t ha⁻¹)</th>
<th>Observed SOC changes (t ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High input without manure (Default)</td>
<td>1.11</td>
<td>47</td>
<td>20.8</td>
<td>25.0</td>
<td>4.3</td>
</tr>
<tr>
<td>NF Crotalaria</td>
<td>1.13</td>
<td>47</td>
<td>20.8</td>
<td>25.5</td>
<td>4.8</td>
</tr>
<tr>
<td>NF Mimosa</td>
<td>1.49</td>
<td>47</td>
<td>20.8</td>
<td>33.5</td>
<td>12.8</td>
</tr>
<tr>
<td>NF Ricebean</td>
<td>1.19</td>
<td>47</td>
<td>20.8</td>
<td>26.9</td>
<td>6.1</td>
</tr>
<tr>
<td>CF Crotalaria</td>
<td>1.18</td>
<td>47</td>
<td>20.8</td>
<td>26.5</td>
<td>5.8</td>
</tr>
<tr>
<td>CF Mimosa</td>
<td>1.45</td>
<td>47</td>
<td>20.8</td>
<td>32.8</td>
<td>12.0</td>
</tr>
<tr>
<td>CF Ricebean</td>
<td>1.27</td>
<td>47</td>
<td>20.8</td>
<td>28.7</td>
<td>8.0</td>
</tr>
<tr>
<td>High input with manure (Default)</td>
<td>1.44</td>
<td>47</td>
<td>20.8</td>
<td>32.5</td>
<td>11.7</td>
</tr>
<tr>
<td>NF Rice straw</td>
<td>1.35</td>
<td>47</td>
<td>20.8</td>
<td>30.3</td>
<td>9.6</td>
</tr>
<tr>
<td>NF Compost</td>
<td>1.45</td>
<td>47</td>
<td>20.8</td>
<td>32.8</td>
<td>12.0</td>
</tr>
<tr>
<td>CF Rice straw</td>
<td>1.37</td>
<td>47</td>
<td>20.8</td>
<td>30.8</td>
<td>10.1</td>
</tr>
<tr>
<td>CF Compost</td>
<td>1.48</td>
<td>47</td>
<td>20.8</td>
<td>33.5</td>
<td>12.7</td>
</tr>
</tbody>
</table>

Note: Assumed that annual cropland in tropical moist region with low input levels and full tillage converted to high input with/without manure managements for 25 years.

SOCREF: Native reference carbon stock for a tropical moist climate on Ultisol soils

SOC(0): SOC stock at the beginning of the inventory time period (annual cropland with low input levels and full tillage) = SOCREF×0.48 (default $F_{LU}$ for long-term cultivated in tropical moist)×1 (default $F_{MG}$ for full tillage)×0.92 (default $F_I$ for low input)

SOC changes = SOCREF×0.48 (default $F_{LU}$ for long-term cultivated in tropical moist)×1 (default $F_{MG}$ for full tillage)×$F_I$×1 (default $F_I$ for low input)

Observed SOC changes: Actual SOC changes in the experimental field from 1980 to 2005

Source: By authors based on (IPCC, 2006) and the field experimental data.
4 Conclusions

Stock change factor for input of organic matter ($F_I$), representing different levels of C input to soil such as organic material application, crop residue treatment and green manure crop cultivation, was computed with the long-term field experimental data in Lopburi Agricultural Research and Development Center, DOA, Lop Buri Province, Thailand. While the computed $F_I$ of “High input with manure” was within the range of IPCC default $F_I$ value, some of the computed $F_I$ of “High input without manure” was much higher than the IPCC default though it was varied due to the biomass production and nutrient contents of the green manure crops planted as the second crops after corn. The $F_I$ computed by field experimental results can contribute to more accurate estimation of SOC changes in farm land especially in Southeast Asia because the default $F_I$ mostly depends on the experimental data in temperate zones.

The long-term field experiment in the present study has been continued. Since 2011 the experiment has focused the effect of reduced tillage practices on SOC changes and corn yield. The results of the experiment will be used to compute $F_{MG}$ which represents the effects of tillage operations.

Acknowledgements

The authors thank Ms. Achara Nuntagij, Director, Soil Science Research Group, DOA for her supports to the study and staff members of Lop Buri Agricultural Research and Development Center for their dedicated assistance during the field experiment.

References


The expansion of Brazilian agriculture: Soil erosion scenarios

Gustavo H. Merten and Jean P. G. Minella

Abstract

During the next 10 years Brazil’s agricultural area will expand to meet increased domestic and worldwide demand for food, fuel, and fiber. Present choices regarding land use will determine to what degree this expansion will have adverse effects that include soil erosion, reservoir siltation, water quality problems, loss of biodiversity and social conflict, especially around indigenous reservations. This paper presents an up-to-date inventory of soil erosion in Brazil caused by crop and livestock activities and provides estimates based on three different hypothetical land-use scenarios to accommodate the expansion of Brazilian agricultural activity by 2020:

Scenario 1 – expansion of cropping into areas of natural vegetation, without adoption of conservation practices;
Scenario 2 – expansion of cropping into areas of degraded pasture, without adoption of conservation practices;
Scenario 3 – expansion of cropping into areas of degraded pasture, together with conservation practices in 100% of the expanded area. The worst-case scenario involves expansion of agriculture into areas of native vegetation in the Brazilian Savannah (Cerrado) and Brazilian rainforest (Amazon) biomes, and could increase total soil erosion in Brazil (currently about 800 million metric tons a year) by as much as 20%. In the best-case scenario, crop expansion under a conservation agriculture model would utilize currently degraded pasture, especially in the Savannah (circa 40 million hectares), reducing soil erosion in Brazil by around 20%. For this to occur, however, a national soil and water conservation policy needs to be implemented in Brazil to support a sustainable model of agriculture in which the environment can be preserved as much as possible.

Key Words: Land use, Conservation agriculture, Degraded pasture, Soil and water conservation policy

1 Introduction

The world-wide need for increased food and biofuel production has pointed to a scenario in which the use of natural resources must be greatly increased over coming years (Godfray et al., 2010). Against this backdrop, one of the expected consequences is increased soil erosion and sediment yield, with consequent reduction in the productive capacity of soils, changes to aquatic ecosystems (Allin et al., 2002) and problems involving sediment deposition in reservoirs used for hydropower generation (Campagnoli, 2005). In Brazil, the area under grain cultivation increased by 80% between 1996 and 2006, particularly in areas such as the Cerrado (Brazilian Savannah). On the other hand, there was a decrease in cattle grazing area in almost all Brazilian states except for Amazon, where it increased by 34% (Merten et al., 2010). Amongst the various causes of increased cattle production, the most im-

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important is the displacement of beef cattle from the Cerrado to the Amazon since pasture areas in the Cerrado can be easily converted to cultivated fields to accommodate soybean expansion (Barona et al., 2010; Brandão et al., 2005).

Although the expansion of agri-business has brought many economic benefits to Brazil, there is an environmental cost to be considered if economic growth is to be environmentally and socially sustainable. Large-scale agricultural activity is generally accompanied by changes in the hydrological regime (Chaves et al., 2008; Costa et al., 2003), loss of biodiversity (Klink & Machado, 2005), and problems with water quality and soil erosion.

The rate of water erosion in Brazil has been estimated to be between 600 and 800 million t yr\(^{-1}\) (Bahia et al., 1992; Hernani et al., 2002), but the contributions from different agricultural activities that add up to this enormous amount are not well-understood. The lack of quantitative information about what each activity contributes makes it difficult to define effective polices for erosion control. For example, of the 237 million hectares of Brazil used for agriculture, 60% is under cultivated pasture or natural rangeland, but little attention has been given to erosion problems in pasture areas since there is a general belief among members of the Brazilian scientific community that pasture areas have low rates of erosion (Sparovek et al., 2007). It is also recognized, however, that Brazil has large areas where pasture is degraded, especially in the Cerrado region.

Although there is no consensus about the size and location of such degraded pastures, values of about 36 million ha (Klink & Machado, 2005; Costa et al., 2006) have been suggested. Pastures are considered degraded when soil fertility has been exhausted, so that grazing is reduced and invasive plants of low nutritional quality appear (Carvalho et al., 1990). These areas, especially when found on sandy soils, show clear evidence of erosion channels and gullies linked to the river channel. Restoring degraded pasture to a state of productivity or grain cultivation would contribute not only to reducing the expansion of cattle-ranching into Amazonia but would also allow expansion of national grain production (Freitas & Manzatto, 2002) without the need to convert areas currently under native vegetation. But for this to happen, a model for sustainable agriculture needs to be adopted in Brazil; a model that should not only meet short-term economic goals but which would also take into account social interests, environmental preservation (biodiversity and water resources), and maintain national security (provision of hydro-power and food) in the medium and long term. The purpose of this paper is to analyze the dynamics of land use and settlement in agricultural areas of Brazil through an inventory of the contributions of different farming activities to erosion, with consideration of different expansion scenarios in agricultural activity expected over the next ten years. Based on this survey, some suggestions are put forth for the introduction of public policy for sustainable agricultural development.

2 Research methodology

Estimates of water erosion were obtained by using the average values of erosion rates per crop given in Table 1, together with agriculture land use data provided by the Brazilian Geographical and Statistical Institute IBGE (2009). In the case of cotton, sugar-cane, cassava and degraded pasture (Table 2), data on erosion rates were derived from experimental studies outside Brazil, since no other information was available for these crops. Such information was sought, however, for regions with climate and soil similar condition to those of Brazil. For degraded pasture, a value of 12 t ha\(^{-1}\) yr\(^{-1}\) was based on information shown in Table 2. It can be seen from this table that rates of soil loss from degraded pasture are 30 times greater than those from non-degraded pastures. Thus the erosion rate from degraded pasture was taken to be thirty times greater than the 0.4 t ha\(^{-1}\) yr\(^{-1}\) found experimentally in Brazil.

The estimated expansion of cultivated area by the year 2020 was based on projections of planned needs for grain and bio-fuel given by Schlesinger (2008). To define land use and soil management in 2020, three scenarios were considered, as well as the present situation;
Table 1: Areas under cultivation in Brazil in 2009, and areas estimated for the year 2020, with erosion rates under cropping systems and soil management, and sources of reference for rates of water erosion

<table>
<thead>
<tr>
<th>Crop</th>
<th>Cultivated area in 2009 (ha)</th>
<th>Projected cultivated area in 2020 (ha)</th>
<th>Estimated soil erosion using conventional tillage (t ha⁻¹)</th>
<th>Estimated soil erosion using no-till (t ha⁻¹)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean¹</td>
<td>21,750,468</td>
<td>35,750,468</td>
<td>6.0</td>
<td>0.6</td>
<td>Hernani et al. (1999)</td>
</tr>
<tr>
<td>Corn</td>
<td>13,659,776</td>
<td>14,000,000</td>
<td>7.0</td>
<td>0.7</td>
<td>Castro et al. (1986)</td>
</tr>
<tr>
<td>Rice²</td>
<td>1,436,018</td>
<td>1,436,018</td>
<td>8.0</td>
<td></td>
<td>Dedeeck et al. (1986)</td>
</tr>
<tr>
<td>Wheat</td>
<td>2,430,253</td>
<td>2,430,253</td>
<td>6.0</td>
<td>0.6</td>
<td>Hernani et al. (1999)</td>
</tr>
<tr>
<td>Sugar cane³</td>
<td>8,514,365</td>
<td>12,200,000</td>
<td>13.0</td>
<td></td>
<td>El-Swaify &amp; Cooley (1980)</td>
</tr>
<tr>
<td>Coffee</td>
<td>2,430,088</td>
<td>2,430,088</td>
<td>4.0</td>
<td></td>
<td>Prochnow et al. (2005)</td>
</tr>
<tr>
<td>Manioc</td>
<td>1,760,578</td>
<td>1,760,578</td>
<td>8.5</td>
<td></td>
<td>Lal (1990)</td>
</tr>
<tr>
<td>Pasture</td>
<td>136,570,658</td>
<td>136,570,658</td>
<td>0.4</td>
<td></td>
<td>Bertoni &amp; Lombardi (1990)</td>
</tr>
<tr>
<td>Degraded pasture⁴,⁵</td>
<td>35,762,415</td>
<td>15,406,556</td>
<td>12.0</td>
<td></td>
<td>Several authors (see Table 2)</td>
</tr>
<tr>
<td>Cotton</td>
<td>811,686</td>
<td>3,141,686</td>
<td>6.2</td>
<td>3.0</td>
<td>Lal (1990); Reisch &amp; Kniigh (2001)</td>
</tr>
<tr>
<td>Tobacco</td>
<td>443,239</td>
<td>443,239</td>
<td>17.2</td>
<td></td>
<td>Merten et al. (2010)</td>
</tr>
<tr>
<td>Others</td>
<td>1,625,154</td>
<td>1,625,154</td>
<td>15.0</td>
<td></td>
<td>Hernani et al. (2002)</td>
</tr>
</tbody>
</table>

² Cultivated area of rain-fed rice.
³ Cultivated area in 2009 given by IBGE (2009) and expansion as given by Schlesinger (2008).
⁵ Degraded pastures from 2009 to 2020 are expected to be reduced to accommodate expansion of soybeans, corn, sugar-cane and cotton (FIESP, 2012).

Table 2: Rates of measured soil loss in areas of degraded (D) and non-degraded (ND) pasture in different countries of the world

<table>
<thead>
<tr>
<th>Place</th>
<th>Biome</th>
<th>Pasture management</th>
<th>Erosion plot size or method</th>
<th>Soil loss (t ha⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Madagascar</td>
<td>Humid Tropic</td>
<td>ND</td>
<td>watershed</td>
<td>0.03</td>
<td>Fournier (1967)</td>
</tr>
<tr>
<td>Kenya</td>
<td>Savannah</td>
<td>D</td>
<td>watershed</td>
<td>53.3</td>
<td>Barber (1983)</td>
</tr>
<tr>
<td>Kenya</td>
<td>Savannah</td>
<td>ND</td>
<td>watershed</td>
<td>1.1</td>
<td>Barber (1983)</td>
</tr>
<tr>
<td>Texas</td>
<td>Prairie</td>
<td>ND</td>
<td>watershed</td>
<td>0.012</td>
<td>Bennett et al. (1954)</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>Prairie</td>
<td>ND</td>
<td>watershed</td>
<td>0.22</td>
<td>Bennett et al. (1954)</td>
</tr>
<tr>
<td>Nepal</td>
<td>Prairie</td>
<td>D</td>
<td>watershed</td>
<td>35</td>
<td>Fleming (1983)</td>
</tr>
<tr>
<td>South Africa</td>
<td>Prairie</td>
<td>D</td>
<td>plots</td>
<td>6.5</td>
<td>Dlamini et al. (2011)</td>
</tr>
<tr>
<td>Zambia</td>
<td>Savannah</td>
<td>ND</td>
<td>Cesio 137</td>
<td>2.5</td>
<td>Collins et al. (2001)</td>
</tr>
<tr>
<td>Kenya</td>
<td>Savannah</td>
<td>ND</td>
<td>watershed</td>
<td>1</td>
<td>Dune (1979)</td>
</tr>
<tr>
<td>Brasil</td>
<td>Savannah</td>
<td>ND</td>
<td>plots</td>
<td>0.1</td>
<td>Dedeeck et al. (1986)</td>
</tr>
<tr>
<td>Brasil</td>
<td>Atlantic Forest</td>
<td>ND</td>
<td>plots</td>
<td>0.4</td>
<td>Bertoni &amp; Lombardi (1990)</td>
</tr>
</tbody>
</table>

D = degraded; ND = non degraded.

a) Scenario 1 – expansion of cropping into areas of natural vegetation, without adoption of conservation practices;
b) Scenario 2 – expansion of cropping into areas of degraded pasture, without adoption of conservation practices;
c) Scenario 3 – expansion of cropping into areas of degraded pasture, together with conservation practices in 100% of the expanded area.

Here, conservation practices are taken to mean a system of soil management based on no-till contour planting, with crop residues of at least 4 t ha\textsuperscript{-1} dry matter preserved, combined with control of surface runoff (Bernardi et al., 2003). In such conditions, expected soil loss is less than 1 t ha\textsuperscript{-1} yr\textsuperscript{-1}.

3 Results and conclusions

3.1 Total erosion

The estimated erosion from different crops listed in Tables 1 and 2, and summarized in Table 3, shows that present-day total erosion from cultivated areas of Brazil is approximately 847×10\textsuperscript{6} t yr\textsuperscript{-1} (Fig. 1). This Fig. is of the same order of magnitude as that given by authors of other research reports Bahia et al. (1992) and Hernani et al. (2002). However these authors assumed a single rate for all crops (15 t ha\textsuperscript{-1}) and a single rate for all pasture areas (0.4 t ha\textsuperscript{-1}).

![Fig. 1: Highly eroded fields in southern Brazil cultivated with no-till, where soil erosion is caused by low residue density, compacted soils and absence of terraces. Source: EMATER-PARANA.](image)

3.2 Erosion per crop type

Erosion estimates for each type of crop are given separately in Table 3. It is important to emphasize that the area of degraded pasture (Fig. 2) contributes 50% of total water erosion caused by agricultural activity in Brazil, followed by sugar-cane (13%), soy (8.5%), maize, corn (6%) and non-degraded pasture (6.5%). These results indicate that development of any soil-erosion policy in Brazil requires the inclusion of degraded pasture in any program for research and extension, since it is of fundamental importance if a national program for erosion control and sediment production is to be defined Sparovek et al. (2007).

Sugar cane contributes significantly to the enormous total soil loss (Fig. 3), the main factor in this case being the high rate of erosion (13 t ha\textsuperscript{-1}), rather than the area planted (7×10\textsuperscript{6} ha). Soybean has the largest of any crop-
ping areas \((21 \times 10^6 \text{ ha})\) but makes only a minor contribution to Brazil’s total soil loss. There are two explanations for the smaller contribution from soybean: erosion rates are smaller \((6 \text{ t ha}^{-1})\) and no-till planting is used in about 50% of the area planted to soybean and maize, leading to erosion rates lower than \(1 \text{ t ha}^{-1}\). It must be emphasized that this value of \(1 \text{ t ha}^{-1}\) can be expected only if no-till planting is performed according to the recommended practice of planting across the slope, with previous crop residues greater than \(4 \text{ t ha}^{-1}\) of dry matter maintained in place to control surface runoff. Another important issue to be emphasized is the relative importance of erosion by different crops in different regions. The figures given in Table 3 show the relative importance between crops for Brazil as a whole. It is recognized, however, that the values for each crop may vary from region to region because of differences in soil, topography, climate and systems of soil management. On the other hand, this does not invalidate the proposition advanced in this paper, which is to draw attention to the relative magnitudes of erosion associated with different agricultural activities. The lack of information about erosion rates and sediment yield for the main agricultural cropping systems in Brazil suggests the need to establish a study network in different Brazilian biomes to monitor soil and water losses at different spatial scales. As well as providing information on these erosion rates, such studies would be useful for calibrating and validating mathematical models for estimating soil loss and sediment yield.

3.3 Erosion by scenario

The expansion in areas under cropping and livestock production in Brazil is expected to reach \(20 \times 10^6 \text{ ha}\) in the year 2020, with particular increases for soybean \((14 \times 10^6 \text{ ha})\), sugar cane \((4 \times 10^6 \text{ ha})\) and cotton \((2 \times 10^6 \text{ ha})\). Amongst the possible scenarios, the worst would be the planting of crops on land that has not yet been brought into cultivation, in particular land under original vegetation in the Brazilian savannah (Cerrado). If this were to happen, total erosion in Brazil would increase by about 20%, with adverse effects on natural resources and loss of biodiversity, hydrological change, reduced water quality, and increased release of greenhouse gases from vegetation burned during clearance.
In Scenario 2, the expansion of agriculture would occur in areas of degraded pasture. The area used for agriculture would remain the same (236×10^6 ha) and total erosion in Brazil would be reduced by 11%, without the need to bring under cultivation any areas presently under natural vegetation.

Scenario 3 would be similar to Scenario 2, but with soil conservation practices used throughout 100% of the areas. Total erosion in Brazil would be reduced by 20%, there would be no additional environmental damage, and no need to clear new areas for cultivation.

The figures given in Table 3 show that it would be possible for Brazilian agriculture to meet projected demands for grain, fiber and bio-fuel by 2020 without expanding agricultural activities into fragile areas such as the Cerrado and Amazon biomes (Scenarios 2 and 3). Furthermore, the different scenarios indicate that it would be possible to actually reduce soil erosion by converting degraded pasture into grain production. It should also be pointed out that this would not require changes to the Brazilian Forest Code BFC Brasil (2013) which have been proposed by some sectors of Brazilian society who argue that this Code needs to be changed to accommodate the expansion of agribusiness in Brazil. The BFC is one of the most advanced pieces of environmental legislation in Brazil. Under it, riparian vegetation is protected by Federal law and cannot be converted to agricultural use. BFC rules also require that all agricultural properties exclude at least 20% of their area from annual crops, or 80% in the northern region. The BFC is important for preserving the nation’s rivers, since riparian vegetation increases the resistance of river banks to erosion processes and also reduces the transfer of sediment and pollutants to river channels (McInnis & McIver, 2009) as shown in Fig. 4. The obligation to maintain part of each property free from intensive cultivation allows areas that are most susceptible to erosion to be conserved.

Agriculture occupies 25% of Brazil, and with growing demand for agricultural products in the international...
market this percentage is expected to be stable in coming years (FIESP, 2012). It has been suggested that extending agricultural activity to more than 20% of areas under natural vegetation could bring about irreversible and adverse environmental changes (Rockstrom et al., 2009) such as, for example, alterations to nitrogen and phosphorus cycles, carbon, and pesticides. Besides the environmental consequences that accompany the expansion of areas producing crops for export, social stresses to the local population are also generated by land use conflict. This happens, for example, when Brazilian agribusiness encroaches on indigenous reserves where Indians have claimed that agricultural activities are polluting the water and destroying the health of stream habitats (Hoffman & Grigera, 2013).

Impacts on water resources arising from agricultural activity in the Cerrado must also be taken into account, since the headwaters of important rivers draining both to the Amazon basin and to the Pantanal region lie within it. In the Pantanal biome, especially, the impacts of agriculture in the Cerrado biome have already been observed, with increased suspended sediment and the presence of agricultural chemicals in Pantanal Rivers (Bordas, 1966). On the map of sediment yield within Brazil the areas with greatest susceptibility to sediment yield lie within the Cerrado. Increased sediment yield in Cerrado Rivers will provoke serious problems of sedimentation in important hydropower plants, both currently in operation and still under construction, in the drainage basins of the rivers Tapajos, Xingu and Tocantins.

Brazil needs to reconcile economic growth with the preservation of natural resources. If this objective is to be attained, it will be necessary to adopt a public policy of conservationist planning for the use of natural resources. Within the context of developing sustainable agriculture in Brazil, the passage of legislation for soil conservation should be considered, along the lines that are now appearing in some Brazilian States such as Paraná and São Paulo, where agricultural activities that lead to soil degradation may be punishable by law. Together with conser-
vationist legislation, the creation of a permanent conservation program for natural resources is needed, to provide technical and financial resources to support of conservationist actions. In the case of agricultural activities, a conservationist agricultural model should be based on the premise that each agricultural holding should have access to a conservation plan approved and overseen by a competent authority. This conservation plan should include demarcation of areas that meet BFC requirements (preservation of riparian environments and of areas most susceptible to erosion), and submission of a conservation plan for cultivated areas. This plan should be based on three fundamental principles: increasing soil cover [by minimizing cultivation (Figs. 5, 6 and 7), use of crops which cover the soil, maintaining forest and pasture], control of surface runoff (by terracing and grass waterways where is necessary); diminished use of agro-chemicals through integrated practices for the control of insects, diseases and invading plants; and control of effluents produced by animal production. To maintain such a program, it will be necessary to create a national budget for the preservation of natural resources, with the power to draw its funding through a tax on a percentage of exported agricultural products (at present, Brazilian law exempts some exported items from payment of tax). Co-ordination of the program should involve the official rural extension service of each Brazilian State. The motivation for farmers to take part in the soil conservation program could be through payments to them, or to watershed associations that would administer environmental services such as maintaining water quality, preservation of water bodies, and reduction of carbon emissions, along the lines of the program “Farming and Water Yields (Agricultor Produtor de Água)” (PAPA, 2013) and “Low-Carbon Agriculture-ABC” (PABC, 2013).

Fig. 5 Soybean planting in the Brazilian Savanna using no-till with millet straw

Source: Eloy Panachuki.

Brazil must be regarded as an important producer of foodstuffs both for its own domestic needs and for the world market as well establishing a national bio-fuels program in order to diversify its energy framework. However, depending on how agricultural expansion occurs, an increase in soil erosion (currently 800 million t yr⁻¹) is expected, with degraded pasture, sugarcane and soybeans (in order of importance) representing the main contributors. The worst-case scenario involves expansion of agriculture into areas of native vegetation in the Brazilian Savanna (Cerrado) and rainforest (Amazon) biomes and could increase total soil erosion in Brazil by as much as
20%.

Under the best-case scenario, crop expansion under a conservation agriculture model would utilize currently degraded pasture, especially in the Savannah (circa 40 million hectares), reducing soil erosion in Brazil by around 20%. In this last scenario, in addition to positive benefits in controlling soil erosion, other important environment problems such as deforestation in the Amazon to accommodate beef cattle expansion and destruction of the Savannah to accommodate soy expansion could be averted. For this to occur, however, a national soil and water conservation policy needs be implemented in Brazil to support a sustainable model of agriculture in which the environment can be preserved as much as possible.

Table 3  Estimated erosion from cultivated areas in 2009 and for Scenarios 1 (S1), 2 (S2) and 3 (S3)

<table>
<thead>
<tr>
<th>Cultures</th>
<th>2009</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybeans</td>
<td>72</td>
<td>156</td>
<td>150</td>
<td>80</td>
</tr>
<tr>
<td>Corn</td>
<td>53</td>
<td>55</td>
<td>55</td>
<td>53</td>
</tr>
<tr>
<td>Beans</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Rice</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Wheat</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>111</td>
<td>159</td>
<td>159</td>
<td>159</td>
</tr>
<tr>
<td>Coffee</td>
<td>10</td>
<td>13</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Cassava</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Cultivated forest</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Pasture</td>
<td>55</td>
<td>55</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Degradated pasture</td>
<td>429</td>
<td>429</td>
<td>185</td>
<td>185</td>
</tr>
<tr>
<td>Cotton</td>
<td>5</td>
<td>19</td>
<td>19</td>
<td>12</td>
</tr>
<tr>
<td>Tobacco</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Others</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Total</td>
<td>848</td>
<td>1,002</td>
<td>752</td>
<td>673</td>
</tr>
</tbody>
</table>
Fig. 7  Sugar cane plants in Sao Paulo state cultivated with no-till using Crotalaria juncea as cover crop

Source: Denizart Bolonhezi.

Acknowledgements

The authors would like to thank Elena Metcalf on your valuable contribution to improving this article. The authors would like to thank to Fundaビジon AGRISUS and CNPq-Conselho Nacional de Desenvolvimento Cientifice e Tecnol vigico Programa Ciencia Sem Fronteiras.

References


Effects of tillage practices on nutrient loss and soybean growth in red-soil slope farmland

Yang Jie¹, Zheng Haijin², Chen Xiaoan³, and Shen Le⁴

Abstract

Field experiments were conducted to examine the effect of tillage practices on sediment and nutrient loss and soybean growth under natural rainfall conditions. Three tillage practices were applied: downslope ridge (check), downslope ridge + contour living hedgerow, and cross ridge. Cross ridge tillage reduced surface runoff by 69% and sediment yield by 86%, compared to the check treatment. The downslope ridge with a contour living hedgerow reduced surface runoff by 24% and sediment yield by 53%. Additionally, compared to the check plot, nutrient losses carried by runoff were reduced by over 68% and that carried in the sediment was reduced more than 85% in the cross ridge plot. Nutrient losses in runoff were reduced by 20% to 30% in the downslope ridge and contour living hedgerow plot and those carried in the sediment were reduced by 44% to 57%. Cross ridge tillage soybean yields exceeded those of the downslope ridge and downslope ridge + contour living hedgerow treatments by 16%–18%. Cross ridge tillage could contribute to the prevention sediment and nutrient loss and could improve crop yield, and thus it is recommended to be applied to mild slopes in the red soil region.

Key Words: Red soil, Slope farmland, Tillage practices, Nutrient loss, Crop growth

1 Introduction

Sloping farmland is an important resource, and also a major source of soil and water loss in China. In recent years, with the increased use of sloping farmland and chemical fertilizer, soil and water loss and non-point source pollution on sloping farmland caused by agricultural activities are gradually coming into focus (Quan & Yan, 2002; Zhu et al., 2005). In-depth systematic studies of the effect of tillage practices on soil erosion, nutrient loss, and crop growth under natural rainfall conditions could not only provide technical support for soil and nutrient loss control and agricultural non-point source pollution control and prevention, but also offer a theoretical basis to the forecast of land productivity and crop yields, which is of great significance.

There have been a large number of studies on soil erosion and non-point source pollution on sloping farmland in terms of characteristics of runoff and sediment yield, law and influencing factors of nutrient loss, and control and prevention measures of soil erosion and water loss (Guo et al., 2010; Lin et al., 2010; Zhao et al., 2004; Lin et al., 2007; Li et al., 2003; Wang et al., 2010; Huang et al., 2007; Wang et al., 2010; Luo et al., 2007), but

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³ Junior Engineer, Jiangxi Institute of Soil and Water Conservation, Jiangxi Provincial Key Laboratory of Soil Erosion and Prevention, Nanchang, China
studies on the impacts of different tillage practices on nutrient loss and crop growth on sloping farmland of red soil is still relatively rare. Crops are mainly soybeans, peanuts and other cash crops on the red-soil sloping farmland in Jiangxi Province, China. For this study, standard runoff plots were built on red-soil sloping farmland in Jiangxi Province where soybeans were planted, and agricultural management was carried out fully in accordance with the practices of local farmers. Surface runoff, sediment loss, nutrient loss and crop growth were measured on plots with different tillage practices to provide a scientific basis to guide the development and use of red soil sloping lands and to provide information useful for the control and prevention of agricultural non-point source pollution in the red-soil region in southern China.

2 Research methodology

2.1 Site description

The study site was in Jiangxi Ecological Science and Technology Park of Soil and Water Conservation. The science and technology park is located in the Yangou Watershed of the Poyang Lake Basin, in De’an County of northern Jiangxi Province, China (115°42’38“–115°43’06“E, and 29°16’37“–29°17’40“N). The site is in the subtropical monsoon climate zone. The mean annual rainfall is 1,350 mm. The mean annual temperature is about 17°C. The annual sunshine duration is 1,650 to 2,100 hours. The average annual frost-free period is 249 days. The landform is low hills, with an altitude of 30 to 100 m, slope of 5° to 25°. The soil parent materials are primarily Quaternary red clay, and the zonal vegetation is subtropical evergreen broadleaf forest. This park is situated in the center of red soil in China, the topography and soil conditions of which are representative of Jiangxi Province and the red-soil region of southern China.

2.2 Experiment design

Nine standard runoff plots with a slope of 10°, were installed on the same slope where soil thickness, physical and chemical characteristics and slope grades are relatively uniform. Each plot was 100 m² in size (20 m×5 m). To prevent surface runoff from flowing into and out of the plots, each plot was surrounded by a 12 cm thick boundary ridging made of concrete bricks, 20 cm above the surface and 30 cm underground. There were rectangular collecting channels and circular collecting tanks below each plot to collect runoff and sediment. Three collecting tanks were designed for each plot, namely A, B and C, according to the local maximum 24-hour storm and runoff volume once in 50 years that may occur. They were made of stainless steel, 1 m in diameter and 1.2 m in height, and the water inlets were 1 m high. Tank A and B had 5 circular flow-dividing holes around the tank walls by “five-group” method, and four groups of contents in tank A were discharged and one group flowed into tank B; like A, four groups of contents in tank B were discharged and one group flowed into tank C. The flow-dividing holes were all 0.8 m high. Each tank was calibrated. Gauges were stuck on the tank walls to observe the water level. In order to facilitate runoff discharge, a circular hole with a diameter of 10 cm and a rubber valve were set on the bottom of each tank.

According to the common local management mode of soybean planting on slope farmland, three treatments, each with 3 replications, were randomly located on the slope. Soybeans were planted on June 18, 2011 and harvested on October 3, 2011 on each plot except control plot (nudation plot). Experimental treatments and design are elaborated in Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Treatments and design of the experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment number</td>
<td>Tillage</td>
</tr>
<tr>
<td>I</td>
<td>downslope ridge (control)</td>
</tr>
</tbody>
</table>

Continued

<table>
<thead>
<tr>
<th>Treatment number</th>
<th>Tillage</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>downslope ridge+contour</td>
<td>Ridge width was 70 cm, and height was 30 cm. Soybeans were planted with 20 cm of spacing in the rows and 35 cm of spacing between the rows on the ridge. Tillage practice was downslope ridge tillage. Contour living hedgerows of day lilies were located every 5 meters on the slope, and there were 2 rows in each hedgerow, with 20 cm of spacing between the rows and 20 cm of spacing in the rows. The day lilies were planted by seedling transplant.</td>
</tr>
<tr>
<td>III</td>
<td>cross ridge</td>
<td>Ridge width was 70 cm, and height was 30 cm. Soybeans were planted by 20 cm of spacing in the rows and 35 cm of spacing between the rows on the ridge. Contour cross ridge tillage was the tillage practice.</td>
</tr>
</tbody>
</table>

2.3 Observation objects and measurement methods

Runoff and sediment yield and nutrient loss were measured after individual rainfalls that caused runoff. Crop growth and production were measured at harvest.

(1) Amounts of runoff and soil erosion. Amounts of runoff were recorded by the gauges on the collecting tanks, and amounts of soil erosion were calculated based on water samples where the oven drying method was used to determine sediment concentration.

(2) Nutrient contents in runoff and sediment. After rainfall, when the collecting tanks had been standing for some time, an appropriate amount of runoff liquid was taken from each tank into a plastic bottle and concentrated sulfuric acid stabilizer was added to the liquid for analytical determination, mainly for analyzing N, P and other nutrient contents in runoff. Then an appropriate amount of runoff liquid was taken from each tank during stirring of the tank stored in a plastic bottle for analyzing the sediment content in runoff. At last, the water in the collecting tanks was discharged, and the sediment in the bottom of each tank was put into a plastic bag for analytical determination, mainly for analyzing C, N, P nutrient contents in the sediment. Conventional chemical analysis methods were adopted to determine the nutrient contents in runoff and sediment.

(3) Crop growth and yield indicators. The biomass of soybean when harvested was calculated by dry weight by weighing. Soybean growth indicators were determined through direct measurement.

3 Results and discussion

3.1 Treatment effect on runoff and sediment yield

Runoff and sediment yield on sloping farmland for the 3 plot types are shown in Table 2. Runoff and sediment yields were the greatest in the downslope ridge tillage where runoff was 6.9% of rainfall, and soil erosion was 1,214 t km⁻², demonstrating that irrational use and treatment of sloping farmland was one primary cause of soil erosion and water loss. Compared with the plot treated by downslope ridge tillage, runoff and sediment yields in the plot treated by downslope ridge tillage + contour living hedgerow were reduced by 24.3% and 52.8% respectively, while those in the plot treated by cross ridge tillage were reduced by 68.9% and 85.7% respectively.

This demonstrated that the contour living hedgerow and cross ridge tillage had significant water detention and soil conservation effects. This was because contour living hedgerow and cross ridge tillage could effectively slow down the surface runoff, which would increase seepage, decreasing runoff. The lowered runoff volumes, along with water storage between ridges perpendicular to the slope, would reduce runoff detachment and promote the sediment deposition on the slope and reduce sediment yield.

The experimental observations showed that; the runoff and sediment reduction effects of cross ridge tillage were more obvious than downslope ridge tillage + contour living hedgerow. One reason was that cross ridge tillage could play a role in soil and water conservation earlier in the year through the interception effects of ridges while the water detention and soil conservation effects of day lily hedgerows will gradually appear with the growth of plants. The runoff reduction effects of downslope ridge tillage with the hedgerow were not as good as its sediment...
reduction effects, which might be because the hedgerow mainly played a role in intercepting runoff, reducing runoff velocity, and trapping sediment in the early growth stage, and therefore it posed more significant impacts on sediment yield than runoff yield.

A detailed analysis of the runoff and sediment yields for each rainfall in each plot during the experimental period revealed that the storm rainfall on August 22, 2011 (precipitation amount of 35.3 mm, rainfall duration of 315 min) caused serious soil erosion and water loss in all plots. The downslope ridge plot, downslope ridge + contour living hedgerow plot and cross ridge plot had surface runoff volumes of 0.60 m³, 0.45 m³, and 0.20 m³, and sediment erosion amounts of 77.2 kg, 41.9 kg, and 16.8 kg, respectively. The runoff volume caused by this intense rainfall was about 60% of the total runoff volume in the experimental period across all treatments. Sediment yield from this single storm ranged from 63% of the total erosion occurring on the downslope ridge plot to 96.9% of the erosion occurring on the cross ridge plot. It was thus clear that it were only a small number of heavy rainfalls that made larger contributions to soil erosion and water loss on sloping farmland. It is important when developing sloping farmland to select crops whose harvest and planting times are not in a period with heavy rainfalls, thus avoiding serious soil and water loss.

### Table 2 Runoff and sediment yield for each treatment

<table>
<thead>
<tr>
<th>Tillage</th>
<th>Runoff</th>
<th>Sediment</th>
<th>Soil erosion modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface runoff (m³)</td>
<td>Runoff reduction (%)</td>
<td>Runoff coef. (%)</td>
</tr>
<tr>
<td>Downslope ridge</td>
<td>1.02a*</td>
<td>—</td>
<td>6.9a</td>
</tr>
<tr>
<td>Downslope ridge + contour living hedgerow</td>
<td>0.77a</td>
<td>24.3</td>
<td>5.2a</td>
</tr>
<tr>
<td>Cross ridge</td>
<td>0.32b</td>
<td>68.9</td>
<td>2.1b</td>
</tr>
</tbody>
</table>

* Treatments with different letters were significantly different (P = 0.05).

### 3.2 Treatment effect on nutrient loss

Nutrients carried by runoff and sediment are major components of soil nutrient loss. The loss of nutrients carried by runoff under different treatments is shown in Table 3. According to Table 3, nutrients carried by runoff in downslope ridge tillage + contour living hedgerow plot and cross ridge tillage plot were both smaller than that in the downslope ridge tillage plot, and the interception efficiencies (defined as the reduction in loss for downslope ridge tillage + contour living hedgerow or cross ridge tillage and downslope ridge tillage) for total phosphorus, total nitrogen, and ammonia-nitrogen in plots with the two former tillage treatments were 28.3%–73.6%, 20.9%–71.4%, and 30.3%–68.6% respectively. While both contour living hedgerow and cross ridge tillage significantly reduced nutrient loss, the cross ridge tillage was the more effective treatment because it had the most effect on runoff. With the growth of day lilies, the interception of nutrients carried by runoff of contour living hedgerow will increase.

### Table 3 Total nutrient losses carried by runoff under different treatments

<table>
<thead>
<tr>
<th>Tillage</th>
<th>Total phosphorus</th>
<th>Total nitrogen</th>
<th>Ammonia-nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Loss (kg km⁻²)</td>
<td>Interception efficiency (%)</td>
<td>Loss (kg km⁻²)</td>
</tr>
<tr>
<td>Downslope ridge tillage</td>
<td>0.14</td>
<td></td>
<td>23.5</td>
</tr>
<tr>
<td>Downslope ridge tillage + contour living hedgerow</td>
<td>0.10</td>
<td>28.3</td>
<td>18.6</td>
</tr>
<tr>
<td>Cross ridge tillage</td>
<td>0.04</td>
<td>73.6</td>
<td>6.7</td>
</tr>
</tbody>
</table>
The loss of nutrients carried by sediment under these treatments is shown in Table 4. The loss of nutrients carried by sediment was less in downslope ridge tillage + contour living hedgerow plot and cross ridge tillage plot than in the downslope ridge tillage plot. As with nutrients in runoff, the losses of nutrients in sediment were much reduced by the contour living hedgerow and the cross ridge tillage. Among the two tillage practices, cross ridge tillage had a higher interception efficiency for total phosphorus, total nitrogen and organic matter (>85%); while the downslope ridge tillage + contour living hedgerow had a lower interception efficiency for nutrients carried by sediment, 44.4% – 56.7%, which reflected the greater sediment reduction effect of cross ridge tillage. With the growth of day lilies, the interception efficiency for nutrients carried by sediment of contour living hedgerow will increase.

Table 4  Total nutrient losses carried by sediment under different treatments

<table>
<thead>
<tr>
<th>Tillage</th>
<th>Total phosphorus</th>
<th>Total nitrogen</th>
<th>Organic matter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Loss (kg km⁻²)</td>
<td>Loss (kg km⁻²)</td>
<td>Loss (kg km⁻²)</td>
</tr>
<tr>
<td></td>
<td>Interception</td>
<td>Interception</td>
<td>Interception</td>
</tr>
<tr>
<td></td>
<td>efficiency (%)</td>
<td>efficiency (%)</td>
<td>efficiency (%)</td>
</tr>
<tr>
<td>Downslope ridge tillage</td>
<td>390.1</td>
<td>701.9</td>
<td>7,646</td>
</tr>
<tr>
<td>Downslope ridge tillage+</td>
<td>217.1</td>
<td>304.2</td>
<td>3,471</td>
</tr>
<tr>
<td>contour living hedgerow</td>
<td>44.4</td>
<td>56.7</td>
<td>54.6</td>
</tr>
<tr>
<td>Cross ridge tillage</td>
<td>53.9</td>
<td>90.6</td>
<td>1,074</td>
</tr>
<tr>
<td></td>
<td>86.2</td>
<td>87.1</td>
<td>86.0</td>
</tr>
</tbody>
</table>

In terms of the forms of nitrogen loss under the different treatments, the loss of nitrogen carried by sediment accounted for more than 94% of the total nitrogen loss, while the loss of nitrogen carried by runoff accounted for less than 6%, indicating that nitrogen loss caused by soil erosion and water loss in sloping farmland was mainly in the form of nitrogen carried by sediment. In terms of the forms of phosphorus loss, the loss of phosphorus carried by sediment under the different treatments all accounted for more than 99.9% of the total phosphorus loss, while the loss of phosphorus carried by runoff occupied was less than 0.1%, phosphorus loss caused by soil erosion and water loss on sloping land was mainly in the form of phosphorus carried by sediment (see Table 5). Therefore, the control and prevention of nitrogen and phosphorus loss using soil and water conservation measures should focus on sediment reduction.

Table 5  Nitrogen and phosphorus loss forms under different treatments

<table>
<thead>
<tr>
<th>Tillage</th>
<th>Proportion of different forms of nitrogen in total nitrogen (%)</th>
<th>Total nitrogen (kg km⁻²)</th>
<th>Proportion of different forms of phosphorus in total phosphorus (%)</th>
<th>Total phosphorus (kg km⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nitrogen carried by runoff</td>
<td>Nitrogen carried by sediment</td>
<td>Phosphorus carried by runoff</td>
<td>Phosphorus carried by sediment</td>
</tr>
<tr>
<td>Downslope ridge tillage</td>
<td>3.2</td>
<td>96.8</td>
<td>725.3</td>
<td>0.03</td>
</tr>
<tr>
<td>Downslope ridge tillage+</td>
<td>5.8</td>
<td>94.3</td>
<td>322.8</td>
<td>0.05</td>
</tr>
<tr>
<td>contour living hedgerow</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross ridge tillage</td>
<td>3.2</td>
<td>96.8</td>
<td>97.4</td>
<td>0.07</td>
</tr>
</tbody>
</table>

3.3 Treatment effect on soybean growth

As shown in Table 6, the biomass of soybean roots, stems, leaves and fruits in the cross ridge tillage plot were greater than those in the downslope ridge tillage plot and downslope ridge tillage + contour living hedgerow plot. Total biomass of cross ridge tillage was 16.2% and 18.8% higher than that of the other two types of plots. Cross ridge tillage increased soybean production, mainly because the interception effect of ridges in cross ridge tillage plot not only reduced runoff velocity, but also directly intercepted and stored large amounts of runoff and sediment,
increasing soil moisture and decreasing nutrient loss on ridges, resulting in the highest soybean biomass. In downslope ridge tillage + contour living hedgerow treatment, as hedgerows took up some area of farmland, soybean planting area was reduced. Meanwhile, in the early growth stage, hedgerows mainly played a role in intercepting runoff, and had a small impact on runoff volume and soil moisture on ridges. Thus, the biomasses of soybean roots, stems, leaves, fruits and the total biomass in downslope ridge tillage plot and downslope ridge tillage + contour living hedgerow plot were similar.

Table 6 Soybean biomass under different tillage practices

<table>
<thead>
<tr>
<th>Tillage</th>
<th>Root mass (g)</th>
<th>Stem mass (g)</th>
<th>Leaf mass (g)</th>
<th>Fruit mass (g)</th>
<th>Total biomass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downslope ridge tillage</td>
<td>3,108</td>
<td>6,839</td>
<td>7,011</td>
<td>10,755</td>
<td>27,713</td>
</tr>
<tr>
<td>Downslope ridge tillage+ contour living hedgerow</td>
<td>3,449</td>
<td>6,122</td>
<td>6,727</td>
<td>10,572</td>
<td>26,870</td>
</tr>
<tr>
<td>Cross ridge tillage</td>
<td>3,707</td>
<td>8,194</td>
<td>8,714</td>
<td>12,473</td>
<td>33,087</td>
</tr>
</tbody>
</table>

According to Table 7, the effective pod number per plant, 100-seed dry weight, average plant height, and average basal stem of soybeans in the cross ridge tillage plot were all higher than those in downslope ridge tillage plot and downslope ridge tillage + contour living hedgerow plot, demonstrating that cross ridge tillage could, to an extent, promote soybean growth. This was because cross ridge tillage could effectively increase soil seepage and soil moisture of ridges through ridges intercepting runoff, therefore the soybeans grew better in cross ridge tillage plot. There were almost no significant differences between the effective pod numbers per plant, 100-seed dry weight, average plant heights, and average basal stem of soybeans in the downslope ridge tillage plot and the downslope ridge tillage + contour living hedgerow plot, likely because the hedgerow could only intercept runoff and slow runoff velocity, and exerted no significant influence on increasing soil moisture of ridges and on promoting soybean growth.

Table 7 Soybean growth index under different tillage practices

<table>
<thead>
<tr>
<th>Tillage</th>
<th>Pods per plant</th>
<th>100-seed dry weight (g)</th>
<th>Plant height (cm)</th>
<th>Basal stem (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downslope ridge tillage</td>
<td>17.0</td>
<td>18.1</td>
<td>47.8</td>
<td>6.2</td>
</tr>
<tr>
<td>Downslope ridge tillage+ contour living hedgerow</td>
<td>17.6</td>
<td>18.5</td>
<td>49.1</td>
<td>6.2</td>
</tr>
<tr>
<td>Cross ridge tillage</td>
<td>18.0</td>
<td>19.6</td>
<td>51.5</td>
<td>6.7</td>
</tr>
</tbody>
</table>

### 4 Conclusion and suggestion

1) In terms of runoff and sediment yields, the analysis of experimental observations indicated that compared to downslope ridge tillage plot, runoff and sediment yields in the plot treated by cross ridge tillage were reduced by 68.9% and 85.7% respectively, while those in the plot treated by downslope ridge tillage + contour living hedgerow were reduced by 24.3% and 52.8% respectively. Therefore, on gentle slopes, microtopography reconstruction by adopting cross ridge tillage treatment and contour living hedgerow treatment can, to an extent, reduce runoff and sediment yields.

2) In respect of nutrient output, the analysis showed that compared with downslope ridge tillage, the interception efficiencies for nutrient carried by runoff and sediment were above 68% and 85% respectively in cross ridge tillage plot, while those were 20.9% - 30.3% and 44.4% - 56.7% respectively in downslope ridge tillage + contour living hedgerow plot. Hence, on gentle slopes, microtopography reconstruction by adopting cross ridge tillage treatment and contour living hedgerow treatment can reduce nutrient loss.
3) For soybean growth, cross ridge tillage increased soybean growth and production; there was no significant
difference in soybean growth and production between downslope ridge tillage and downslope ridge tillage + contour
living hedgerow.

As only a small number of heavy rainfalls made greater contributions to soil and water loss and nutrient loss,
the crops whose harvest and planting times are not in a period of heavy rainfalls should be selected to avoid caus-
ing serious soil erosion and water loss when developing sloping farmland. Overall, the cross ridge tillage had grea-
ter effects on reducing soil erosion and water loss and nutrient loss, and promoting soybean growth on slope farml-
land of red soil than the contour living hedgerow. However, because this experimental cycle was relatively short, the
impacts of living hedgerow on soil, water and nutrient loss and crop production in developing slope land of red soil
needs further observation and in-depth study.

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Rainwater harvesting, its prospects and challenges in the uplands of Talugtog, Nueva Ecija, Philippines

Samuel M. Contreras¹, Teresita S. Sandoval², and Silvino Q. Tejada³

Abstract

The prospects and challenges facing eight small water impounding projects (SWIPs) in Talugtog, Nueva Ecija, an upland municipality located in Central Luzon, Philippines were evaluated using rapid appraisal and documentation of projects, interview of farmers and local officials, and a review of related studies undertaken on the same project sites. The challenges include the deterioration of structural facilities, inactive farmers associations, watershed degradation, and climate change. It also aims to evaluate improvement and innovation in the future implementation of SWIPs as rainwater harvesting facilities. The site was selected because it has the largest number of SWIPs established as one of the coping strategies during the 1997–1998 severe El Niño. Because of its location, it has no major irrigation systems and relies only on local rainwater storage facilities. The study involves 8 SWIPs established in two clusters (i.e., 5 and 3 SWIPs in a watershed) as rainwater conservation and management facilities. Results indicated these clusters of SWIPs offer multiple benefits in terms of supplemental irrigation, inland fish production, and water for domestic purposes and livestock production. They also serve as strategic small-scale upland structures that enhance recharging of groundwater, prevent flooding, and provide value-adding activities such as recreation, soil and water conservation, and environmental benefits. Previous studies also identified their benefits at the farm and community levels as conserved rainwater through storage in SWIPs is translated into more economic uses. However, some SWIPs are confronted with various challenges; deterioration of structural facilities, inactive farmer associations, unabated watershed degradation, and threats of climate change. These are seriously affecting the overall performance of SWIPs. Immediate actions should include the strengthening of small water impounding system associations (SWISA), repair and climate-proofing of structural facilities through the (SWISA) themselves, and watershed protection and management through the adoption of appropriate soil and water conservation measures.

Key Words: Rainwater harvesting, Small water impounding project, Upland, Watershed, SWISA

1 Introduction

In a tropical country such as the Philippines, abundant rainfall is considered a water resource for development and yet it is not fully used due to the seasonality of its occurrence. Rainwater harvesting through small water impounding projects (SWIPs) addresses the unbalanced rainfall distribution by collecting and storing direct rainfall and surface runoff for future use. SWIPs serving as rainwater harvesting and storage structures consist of an earth
embankment, spillway, outlet works and canal facilities. They are usually located in intermittent creeks or watercourses with potential uses for irrigation, fishery, livestock watering, and domestic uses. SWIPs were implemented by the Bureau of Soils and Water Management (BSWM) of the Department of Agriculture as early as the 1950s primarily for soil and water conservation. In 1976, a shift occurred in flood control priorities from traditional protective structures to small-scale impounding reservoirs or retarding basins at the upper reaches of rivers and streams while simultaneously using the impounded water for more productive economic uses.

Aside from economic benefits, SWIPs have an important role in enhancing the multi-functionality of agriculture particularly in the uplands (Concepcion et al., 2006). It offers an opportunity for integrating the various aspects of soil and water movement from the time and place that rain fell as it reached the ground and flowed as run-off or percolated into the groundwater reservoir, or was captured in a surface reservoir, and perhaps was released to lower agricultural landscapes. The results of SWIP performance reviews and assessments in 2002–2003 indicated that some had achieved or even surpassed their expected economic performances. However, there were systems performing below the expected level due to natural, technical and socio-economic factors (Contreras & Samar, 2004). Yet, rainwater harvesting through SWIPs remains one of the key government interventions to contribute to the country’s irrigation development program and an option for climate change adaptation.

Farmers also recognized the importance of SWIPs as they frequently request the establishment of additional SWIPs in their respective areas. As weather becomes more severe and unpredictable due to climate change, a new paradigm in the management of rainwater is required (Han, 2006). This new paradigm involves the development of small scale detention ponds or rainwater storage facilities, instead of large remote projects, with each small scale facility promoting multi-purpose rainwater management rather than single purpose watershed management. Such facilities could not only prevent flooding, but could also reduce the effect of drought with rainwater being conserved for immediate or future use. The case of rainwater harvesting facilities in Talugtog, Nueva Ecija Philippines reflects this new paradigm. Clusters of rainwater harvesting facilities were implemented in previous years through the initiative of the local government unit (LGU) and national government agencies.

Cognizant of the continuing promotion of SWIPs and in reference to this new paradigm, this study analyzes the prospect and challenges of rainwater harvesting as strategic rural infrastructure in the Philippine upland community. It also reviews the multi-purpose nature of SWIPs by evaluating their multi-functionality in terms of socio-economic and environmental services, and their performance over the years of implementation as a basis for the promotion of rainwater harvesting in the Philippine uplands.

2 Research methodology

The methodology involves the gathering of primary and secondary data and reviewing previous studies of SWIPs in Talugtog, Nueva Ecija. For the purpose of this study, the following activities were undertaken:

1. Profiling of SWIPs;
2. Site validation and field inspection;
3. Key informant interview [i.e., with presidents of Small Water Impounding System Associations (SWISA) as respondents];
4. Focus group discussion with local government officials;
5. Assessment of inherent environmental and socio-economic functions of SWIP in the study area;
6. Review of related studies undertaken in the past at the study area.

2.1 Profiling of SWIPs

The profiling of SWIPs in the study area was undertaken based on available records of the LGU of Talugtog, Nueva Ecija. As of June 2013, the municipality had eight SWIPS currently in operation and one under construction. The project profile was reviewed and compared with the BSWM record. Started in 1992, these SWIPs are dist-
tributed in seven neighboring upland local villages. Generally, these villages are not served by any major irrigation system because of their location. They are relying on rainwater harvesting to produce two crops of rice a year.

2.2 Site validation and field inspection

Site validations and field inspections were undertaken by a BSWM team of engineers to determine the operational status of all SWIPs in the study area. Project structural facilities were inspected (i.e., embankment, spillway, outlet works, canal and canal structures, access road, and stored rainwater at the time of the field survey). Point locations of these facilities were marked through a Global Positioning System (GPS) unit and their current physical and functional conditions were assessed. While undertaking the visual assessment, officers of the SWISA were also interviewed to provide additional information to support the documentation and findings of the team.

2.3 Key informant interviews

A simplified interview schedule was prepared for the conduct of field interviews with concerned officers of each SWISA. The following information was collected:

1. General Project Description (i.e., Date of completion, Watershed area including its dominant land use, Reservoir area and capacity, Service area);
2. Physical Status of Major Structures;
3. Irrigation System Information (i.e., Crops planted per cropping and yield, Number of beneficiaries, irrigation service fee, status of irrigation facilities);
4. Other benefits derived from the project and other agri-infrastructures established since the operation of the project.
5. Observed impact of SWIPs;
6. Challenges and problems encountered.

Because written records are limited, the information furnished by the incumbent officers of the SWISA was supplemented and validated by the responses from other key local officials, particularly the Municipal Agriculturist and Agricultural Technicians who monitor agriculture-related activities of a local village.

2.4 Focus Group Discussion (FGD)

More interactions and discussions were also organized through FGD with farmer-leaders, local government officials, and BSWM technical personnel as participants. The discussion primarily centered on the challenges encountered by SWIP during their operation, their socio-economic impacts to the municipality, SWIPs as learning centers for season-long Farmer Field School (FFS), and the added projects implemented in support of the operation and maintenance of each SWIP. The FGD also touched on the problems encountered in project implementation due to lack of proper coordination by implementing agencies with the local government unit. The future plan and program for SWIP expansion was also discussed.

2.5 Assessment of environmental and socio-economic functions of SWIPs

The multiple functions of SWIPs as rainwater harvesting facilities were previously documented as follows:

1. Environmental Functions
   a. Soil and water conservation
   b. Flood mitigation
2. Economic Functions
   a. Supplemental source of irrigation
   b. Inland fish production
   c. Watering of livestock
   d. Domestic purposes
   e. Recreation facility

For the purpose of this study, the environmental function was evaluated through reservoir operation studies
A Reservoir operation study (ROS) is a “water accounting” technique that involves simulated reservoir runs for different extents of service area until the maximum area is attained with minimum reservoir spill or shortage (Concepcion, et al., 2006). ROS was undertaken using a Microsoft Excel spreadsheet prepared by BSWM (2002). The important elements of the ROS include reservoir inflow from the watershed, surface water evaporation from the reservoir, water demand from the irrigated area, and the storage capacity and allocation at different depths in the reservoir. The flood mitigation function of SWIP was assessed through a flood analysis which involved the development of an inflow hydrograph, using the US Soil Conservation Service method, and an equivalent outflow hydrograph (i.e., with the reservoir) through a flood routing analysis as described in the design manual of BSWM (2002).

On the other hand, the socio-economic function was evaluated based on the observed level of use for specific economic purposes as provided by the SWISA and the concerned LGU staff.

2.6 Review of related studies undertaken in the study area

With eight SWIPs implemented in the Talugtog, Nueva Ecija, the municipality has been the subject of several studies in the past. Most looked into the effectiveness of SWIP as a coping strategy against prolonged drought and their importance in enhancing the multi-functionality of agriculture within the context of a watershed. As part of this study, they were reviewed to determine their implications on the future prospects and challenges of rainwater harvesting as one of the adaptation measures against climate change and as a banner program to propel rural development in resource-poor upland communities. Moreover, previous performance assessment of SWIPs (i.e., Contraceñas & Samar, 2004) was also reviewed and relates the results to the recent observations in Talugtog, Nueva Ecija.

3 Results and discussion

3.1 Description of the Study Area

The municipality of Talugtog is a 4th class municipality located in the northern part of Nueva Ecija Province in Central Luzon, about 169 km north of Manila. It is an upland municipality characterized by rolling to hilly topography at the northern portion covering seven local villages at the foot of two mountain ranges. The southern section is characterized by flat to gently sloping topography, which constitutes the main agricultural area of the municipality. Some 67% of the total land area is cultivated, most of which is rainfed with only 18% of the total agricultural area having irrigation facilities. Because of its location, it is not served by any major irrigation system and relies

![Fig. 1 Cropping pattern and calendar and plots of field water balance parameters](image-url)

Note: $E_t+S&P$ - Evapo-transpiration plus seepage and percolation.
only on localized rainwater storage facilities, such as SWIPs.

With an average annual rainfall of 1,905 mm, the study area is characterized by two distinct seasons: dry from November to April and wet the rest of the year. This rainfall pattern is reflected by the prevailing cropping pattern and calendar in which the first crop of paddy rice is planted at the onset of the rainy season in late May and the second crop in November. The dry months of March and April are kept as a fallow period as shown in Fig. 1.

### 3.2 Description and project profile of the eight (8) SWIPs

As shown in Fig. 2, the eight SWIPs are strategically located in the northeastern and southwestern part within the rolling and hilly landscape of the municipality. They could be grouped into a northeastern cluster of five SWIPs and a southwestern cluster of three SWIPs. Visible in Fig. 2 is the nearly level main agricultural area at the southern part of the municipality. The southernmost part is expected to be irrigated in the future through the on-going Cagayan Multi-purpose Project. Table 1 presents the general project profile of each SWIP based on field surveys and available records of SWISA. The projects have watershed areas covering a total of 906 hectares and 67.23 hectares of reservoir area. With a total storage capacity of 3,258,120 m$^3$, the eight SWIPs could provide supplemental irrigation to about 324 ha during the rainy season, 293 ha during the dry season, and 5 ha as third crop (for two SWIPs).

![Satellite imagery showing the location of the clusters of eight SWIP](image)

**Fig. 2 Satellite imagery (Google Earth) showing the location of the clusters of eight SWIP**

<table>
<thead>
<tr>
<th>Name of project</th>
<th>Year completed</th>
<th>Watershed area (ha)</th>
<th>Reservoir area (ha)</th>
<th>Reservoir capacity (m$^3$)</th>
<th>Service area* (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Masiin SWIP</td>
<td>1997</td>
<td>375</td>
<td>22.64</td>
<td>1,505,693</td>
<td>100</td>
</tr>
<tr>
<td>2. Sampaloc SWIP</td>
<td>1993</td>
<td>80</td>
<td>7.00</td>
<td>257,625</td>
<td>40</td>
</tr>
<tr>
<td>3. Buted II SWIP</td>
<td>2001</td>
<td>130</td>
<td>4.20</td>
<td>224,613</td>
<td>40</td>
</tr>
<tr>
<td>4. Buted I SWIP</td>
<td>1995</td>
<td>70</td>
<td>7.84</td>
<td>298,241</td>
<td>50</td>
</tr>
<tr>
<td>5. Trebaga SWIP</td>
<td>2010</td>
<td>100</td>
<td>5.00</td>
<td>190,205</td>
<td>40</td>
</tr>
<tr>
<td>7. Villa Beado SWIP</td>
<td>1999</td>
<td>75</td>
<td>6.19</td>
<td>235,474</td>
<td>50</td>
</tr>
<tr>
<td>8. Sta. Catalina SWIP</td>
<td>1999</td>
<td>36</td>
<td>4.00</td>
<td>152,164</td>
<td>30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>906</strong></td>
<td><strong>67.23</strong></td>
<td><strong>3,258,120</strong></td>
<td></td>
<td><strong>400</strong></td>
</tr>
</tbody>
</table>

* Based on project feasibility study.
3.3 Environmental functions of SWIPs

To assess the environmental functions of SWIP in the study site, two representative SWIPs were studied in terms of amount of rainwater conserved and used (i.e., based on reservoir operation studies) and their ability to reduce peak flood (i.e., based on the result of flood routing). Based on the results of the reservoir operation studies and actual measurement of water level fluctuation in the reservoir, the two representative SWIPs have collected and conserved significant amounts of watershed inflows that would otherwise have directly flowed downstream and may have caused flooding of low lying areas of neighboring municipalities particularly during high intensity rainfall events. Maasin SWIP, during the reservoir operation from June to December 2005 collected and stored about 1.45 million m$^3$ of runoff and rainwater for a period of about 130 days. This measured volume almost coincided with the calculated amount of about 1.20 million m$^3$ using the ROS technique as shown in Fig. 3. The stored rainwater and runoff was then used at the onset of the dry season as indicated by the decline in reservoir storage in November (i.e., the start of the second crop) onward.

Buted II SWIP, was able to collect and store about 0.18 million cubic meters of runoff for a period of only 80 days which is expected considering the smaller reservoir area available for storage. This coincided well with the result of the ROS as shown in Fig. 4 with an equivalent harvested or conserved rainfall and runoff of 0.19 million cubic meters. The actual measurement also indicated that the stored rainwater was only utilized 20 days after the onset of the dry season as farmers utilized the residual rainfall still stored in the paddy field. With the validity of the ROS application to calculate the probable amount of conserved rainwater through SWIP, the flood analysis using reservoir storage allocation applied in the ROS is therefore justified. As revealed in Figures 3 and 4, Buted II reservoir reached its maximum storage capacity on the 23rd decade [i.e., a decade is equivalent to 10 days for the first two decades of the month and 10.9 (in case of February) or 11 (for those months with 31 days)] days for the last decade of the month) of August while Maasin SWIP reached its full storage capacity on the 28th decade of October. This was due to Buted’s limited storage capacity to contain rainwaters during the rainy season. This was confirmed by inflow-outflow hydrographs derived for both sites as shown in Fig. 5. With the incoming flood water routing around the reservoir longer in Maasin SWIP than in Buted SWIP, the flood peak can be reduced by almost 5 times in Maasin SWIP, while it is only about 2 times in Buted II SWIP. The flood prevention function of SWIPs is also reflected in the inflow-outflow hydrograph in terms of the difference between inflow peak discharge and reservoir outflow peak discharge. Maasin SWIP, with its bigger reservoir surface area and storage capacity, could store
more rainwater and therefore has more impact in terms of the flood prevention function. This is further reflected in Fig. 5 as the calculated outflow flood peak discharge (i.e., outflow peak discharge rate in the project un-gated spillway) for Maasin is 11.65 m³ s⁻¹. Without the SWIP, this would be 54.86 m³ s⁻¹ and therefore there is an equivalent reduction of almost 5 times in the peak discharge with the SWIP. In case of Buted II SWIP, the calculated outflow flood peak discharge is 11.00 m³ s⁻¹ and without the SWIP this would be 20.83 m³ s⁻¹ or reduction of just 2 times in the peak discharge.

![Runoff collection period](image)

**Fig. 4** Results of reservoir operation studies (ROS), Buted II SWIP, Wet Season 2005 (Concepcion et al., 2006)

![Inflow-outflow hydrographs](image)

**Fig. 5** Inflow-outflow flood hydrographs of Maasin and Buted II SWIP under maximum flood condition (Concepcion et al., 2006)

### 3.4 Socio-economic functions

Socio-economic benefits from SWIPs can be seen both at the farm and community levels (Monsalud et al., 2002). This recent study revealed that the provision of supplemental irrigation and inland fish production were the prominent functions that contributed to these benefits at most sites. These can be equated to local food security and rural livelihood improvement for the specific village where the SWIP is located and for the whole municipality in general. As shown in Table 2, the eight SWIPs could generate an annual production of about 3,125 tons of palay (palay is rice at any stage prior to husking) which is equivalent to about 2,030 tons milled rice that could feed a-
about 18,500 people (i.e., at 110 kg per capita per year rice consumption) or nearly the entire population of the municipality (i.e., 21,291 people at 2010 census). Fish production is another incidental economic function of SWIP with the total harvest being divided between the land owner of the reservoir area and the SWISA as per agreements between them. Other unaccounted economic functions but also observed in the study area include livestock watering, domestic use (i.e., for washing clothes and cleaning animal pens), and for recreation.

Table 2  
Socio-economic benefits generated by the eight SWIPs, May 2013

<table>
<thead>
<tr>
<th>SWIP</th>
<th>Irrigated Area * (ha)</th>
<th>Ave. Yield (t ha⁻¹)</th>
<th>Ave Annual Production (t)</th>
<th>Other benefits * * * *</th>
<th>No. Of farmer-beneficiaries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st crop</td>
<td>2nd crop</td>
<td>3rd crop</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Maasin</td>
<td>80 **</td>
<td>80</td>
<td>3</td>
<td>5.25</td>
<td>856</td>
</tr>
<tr>
<td>2. Sampaloc</td>
<td>32 **</td>
<td>32</td>
<td>—</td>
<td>6.50</td>
<td>416</td>
</tr>
<tr>
<td>3. Buted II</td>
<td>27</td>
<td>27</td>
<td>2</td>
<td>4.50</td>
<td>252</td>
</tr>
<tr>
<td>4. Buted I</td>
<td>43</td>
<td>37</td>
<td>—</td>
<td>5.15</td>
<td>412</td>
</tr>
<tr>
<td>5. Tebag</td>
<td>30</td>
<td>25</td>
<td>—</td>
<td>4.00</td>
<td>220</td>
</tr>
<tr>
<td>6. Sto. Domingo</td>
<td>50</td>
<td>30</td>
<td>—</td>
<td>4.75</td>
<td>380</td>
</tr>
<tr>
<td>7. Villa Boado</td>
<td>40</td>
<td>40</td>
<td>—</td>
<td>4.75</td>
<td>380</td>
</tr>
<tr>
<td>8. Sta. Catalina</td>
<td>22 **</td>
<td>22</td>
<td>—</td>
<td>4.75</td>
<td>209</td>
</tr>
<tr>
<td>Total/Average</td>
<td>324</td>
<td>293</td>
<td>5</td>
<td>4.96</td>
<td>3,125</td>
</tr>
</tbody>
</table>

* Prevailing cropping pattern: Rice-Rice-Fallow.
** This excludes areas farther downstream that belong to the neighboring municipality but are not members of SWISA.
*** Completely rain-fed because of limited stored water in the reservoir during the period.
**** Fish production (FP) was not properly recorded but could reach 5-10 tons per year based on the estimate of sharing between SWISA and land owner(s) of the reservoir.

3.5 Present status of project structural facilities and project components

With an average age of 14 years (3-21 years), most of the SWIPs studied are near their economic life of 25 years (i.e., except for Tebag SWIP which was only completed in 2010). Yet, their main embankments are still stable and no major structural damage was noted except for a lateral crack observed in Sta. Catalina SWIP every dry season, which is being attended to by the SWISA members. In general, most spillways need regular cleaning and maintenance although farmers observed that they are “rarely used”. Most of the required major repairs are in the outlet works and control gate valves which are either partially functional or need complete replacement due to age. Canal and canal structures are regularly maintained by SWISA members and minor repairs are being addressed through SWISA funds except for Sta. Catalina SWIP (i.e., sinking canal) and Tebag SWIP (i.e., too deep canal and no division boxes) that require major structural works to increase efficiency in their water delivery.

A forest tree plantation was observed downstream of one dam site while the potential benefits of an agro-forestry venture are very visible in another site (Villa Boado SWIP). Existing land cover damaged by forest fire was also observed, particularly in the Maasin SWIP watershed.

Table 3 summarizes the status of project structural components while Fig. 6 shows actual field conditions of these components in May 2013.

3.6 Impacts of SWIP clusters

As shown in Fig. 2, there were two clusters of SWIPs in the study area and it was hypothesized that such arrangements could enhance their environmental and socio-economic functions. In essence, they have impacts in terms of rainwater conservation and in the prevention of localized flooding immediately downstream. The location and distribution of SWIPs in the study area, with the current cluster arrangement could enhance their environmental functions on flood control on the bigger area as the reduction in flood peaks are combined to achieve more sig-

nificant impacts. However, it requires a sufficient number of SWIPs in the upper reaches of the basin to collect and store runoff which when combined will not only prevent flooding but will also mitigate drought and water scarcity.

As revealed by the SWISA officers and LGU officials, the five (5) SWIPs in Cluster 1 complement each other through the following:

1. Use of excess water from SWIPs upstream to supplement the limited capacity of downstream SWIP’s;
2. Provision of water to other SWIPs at critical periods of crop growth at times when water supply is inadequate;
3. Opportunities to share technologies and lessons learned on water management between adjacent SWIPs.

These SWIP clusters also became viable recipients of other agricultural infrastructure facilities and equipment such as multi-purpose drying pavement (MPDP), threshers, hand tractors, flatbed dryers, and pump and engine sets. The municipality is also a recipient of the expanded modified rapid composting project under the organic agriculture program. These SWIPs also became a regular venue of various field trips and training such as season-long Farmer Field School (FFS) organized by the Philippine Rice Research Institute (PhilRice).

### 3.7 Challenges and Constraints

As rainwater harvesting facilities, the 8 SWIPs were also confronted with different challenges during their project operation. Basically, these challenges are technical and institutional in nature as shown in Table 4. Technical issues are mostly related to damaged structural facilities due to age that resulted in inefficient or poor performance of the system. Improperly designed and silted canals were also noted along with watershed degradation, which is slowly affecting water availability. Institutional issues are more SWISA-related in terms of inactive members or inactive SWISA, which negatively influence the overall system operation and maintenance. Recognizing the importance of and benefits from SWIPs on their livelihoods, most SWISA have taken their own initiatives to address those issues in consultation with the Local Government Unit (LGU), as presented in Table 4. Those major repairs and/or replacement of project facilities are being addressed by the Bureau of Soils and Water Management for climate proofing of the structural facilities. In coordination with the LGU, watershed management plans are also prepared to provide long term solutions to watershed degradation problem.

### Table 3: Status of structural components of the project

<table>
<thead>
<tr>
<th>SWIP</th>
<th>Main Embankment</th>
<th>Spillway</th>
<th>Outlet Works</th>
<th>Irrigation Facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maasin</td>
<td>Stable and well-maintained</td>
<td>Side slope scouring</td>
<td>Gate valve loose thread</td>
<td>Operational</td>
</tr>
<tr>
<td>Sampaloc</td>
<td>Stable</td>
<td>Needs cleaning at the approach</td>
<td>With leaks at the pipe conduit-DS</td>
<td>Operational</td>
</tr>
<tr>
<td>Buted II</td>
<td>Stable</td>
<td>Operational</td>
<td>Operational</td>
<td>Low efficiency</td>
</tr>
<tr>
<td>Buted I</td>
<td>Stable and well-maintained</td>
<td>Operational</td>
<td>Dilapidated outlet works; operational</td>
<td>Operational</td>
</tr>
<tr>
<td>Tebag</td>
<td>Stable</td>
<td>Operational</td>
<td>Operational</td>
<td>Some canal sections are too deep; no division boxes</td>
</tr>
<tr>
<td>Sto. Domingo</td>
<td>Stable</td>
<td>Side slope scouring</td>
<td>Operational</td>
<td>Operational</td>
</tr>
<tr>
<td>Villa Boado SWIP</td>
<td>Stable</td>
<td>Operational</td>
<td>Operational</td>
<td>Operational</td>
</tr>
<tr>
<td>Sta. Catalina</td>
<td>Lateral cracking at dam crest observed every dry month</td>
<td>Operational but needs cleaning</td>
<td>Damaged gate valve</td>
<td>Sinking canal above five canal crossings</td>
</tr>
</tbody>
</table>
Fig. 6  Present status of structural facilities and physical project components
Table 4  
Issues and constraints observed and identified by farmer-beneficiaries

<table>
<thead>
<tr>
<th>SWIP</th>
<th>Technical</th>
<th>Institutional/Social</th>
<th>SWISA’s Response to specific issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maasin</td>
<td>Damaged canal; forest fire in watershed</td>
<td></td>
<td>Regular cleaning and maintenance of canal and canal structures; replanting activities</td>
</tr>
<tr>
<td>Sampaloc</td>
<td>Leak in outlet works; limited water supply for first crop</td>
<td></td>
<td>Diversion of waste water through temporary dam at the wayway</td>
</tr>
<tr>
<td>Buted II</td>
<td>Poor canal maintenance</td>
<td>Inactive SWISA officers and members</td>
<td>Re-organize the SWISA and schedule regular canal maintenance</td>
</tr>
<tr>
<td>Buted I</td>
<td>Low canal distribution efficiency; poor quality of fish harvested</td>
<td></td>
<td>2 x a year community work for canal repair and maintenance; to consult BFAR(^1) to improve fish quality</td>
</tr>
<tr>
<td>Tebag</td>
<td>Too deep irrigation canal in some portions</td>
<td></td>
<td>Undertook repair through SWISA members</td>
</tr>
<tr>
<td>Sto, Domingo</td>
<td>Damaged canal resulting in poor water distribution</td>
<td>Catching of fish from the reservoir by non-members</td>
<td>Annual community work to repair damage portion</td>
</tr>
<tr>
<td>Sta. Catalina</td>
<td>Sinking canal section above canal crossings; limited water for first crop</td>
<td></td>
<td>Put sand bags in affected areas thru community work</td>
</tr>
</tbody>
</table>

\(^1\) BFAR-Bureau of Fisheries and Aquatic Resources.

4  Conclusion and recommendation

Rainwater harvesting through small water impounding projects (SWIPs) is well recognized as providing both environmental and socio-economic functions. By collecting and storing rainwater and surface runoff in strategic locations within a watershed, rainwater harvesting can reduce flood peak discharge, the volume and force of runoff and subsequently its eroding power. When established as clusters of small water impoundments, its impacts to prevent not only local flooding but also large scale flooding can be achieved. In addition, the conserved rainwater can be used in more productive and economic applications such as supplemental irrigation and inland fish production. The cluster of SWIPs in Talugtog, Nueva Ecija is a test case to gain the needed momentum to pursue a national policy on rainwater harvesting with participation of local government and strong community-based farmers organization. Putting the local environmental and socio-economic gains and the challenges of Talugtog Nueva Ecija into a national perspective, a future road map on rainwater harvesting should consider the following path:

1. Identify and prioritize critical watersheds where rainwater harvesting could provide a satisfactory environmental and socio-economic impact;

2. Within a watershed, locate potential clusters of sub-watersheds in which to establish small-scale detention ponds or reservoirs such as SWIP as “a first line of defense” against flooding during the rainy season that could be managed by farmers for multiple economic uses during the dry season;

3. Strengthen local government unit participation on rainwater harvesting programs and encourage private sector involvement;

4. Intensify public awareness through education campaigns to gain support and advocacy from all sectors; and

5. Establish a monitoring mechanism to determine the long term environmental and socio-economic impacts of rainwater harvesting with the new paradigm of clustering SWIP within a watershed as a new direction for development.

References


Mulching as a mitigation agricultural technology against land degradation in the wake of climate change

Bhanooduth Lalljee1

Abstract

The sloping topography of the island of Rodrigues (an outer island dependency of the Republic of Mauritius) makes it very prone to soil erosion, and loss of fertile topsoil. Climate variability and climate change in the form of increasing temperatures, long periods of drought followed by short periods of torrential rains are exacerbating this situation. Mulching is a cheap, affordable, sustainable agricultural technology for sustainable soil and land management and reducing soil erosion, which can be adopted by small as well as large farmers. The present work on mulching was carried out in Rodrigues in farmers’ fields that were prone to severe soil erosion (8% slope) Banana (Musa sp) leaves, coconut (Cocos nucifera) leaves, and vetiver (Vetiveria zizanoides) grass, at 0 t ha⁻¹, 10 t ha⁻¹, 20 t ha⁻¹ and 40 t ha⁻¹, were used as natural organic mulches after seeding the plots with maize in a randomised block design with four replicates. Runoff and sediment were collected from the treated and control plots, and analysed for total sediments, total runoff, and nutrient content (N, P, K). Results showed that all the mulches tested contributed to lowering of soil and nutrient losses, albeit in varying amounts. Coconut leaves mulch was found to be the most efficient, followed by vetiver and then banana leaves. Percentage mitigation in soil and nutrient erosion was found to be 28.9% for banana leaves at 10 t ha⁻¹, and 57.3% for coconut leaves at 40 t ha⁻¹. The reduction of soil and nutrient losses was attributed to the mechanical barrier provided by the mulches, and also to the reduction in the momentum of raindrops acting on the soil aggregates. Mulching also contributed to increasing infiltration rate, lowering temperature and therefore lowering evaporation.

Key Words: Erosion, Mulch, Runoff, Sediment, Nutrient losses

1 Introduction

Mulching, which consists of covering the soil surface with organic material (and sometimes inorganic materials), is an age-old practice (Jacks et al., 1955) and was used to control soil moisture, soil temperature, nutrient loss, salinity, erosion soil structure, etc. However, with modern agriculture, this practice dwindled largely, but is now gaining importance once again in the context of sustainable agriculture. In the wake of climate change, high temperature, land slides, flashfloods, etc., mulching has regained its importance. Various types of mulches have been demonstrated to reduce soil erosion by more than 90% compared to bare agricultural soil (Mostaghini et al., 1994).

The need for increasing food security, while at the same time improving the quality of the environment, has prompted the search for materials that can protect the soil and maintain soil health (Armbrust & Jackson, 1977).
Mulches such as straw have been shown to increase plant growth (Badia & Marti, 2000; Peterson et al., 2009). Similarly, mulch cover has been positively correlated with plant cover and plant species richness (Dodson & Peterson, 2010). According to one report, soil erosion is second only to population growth as the biggest environmental problem that threatens agriculture in Africa and, to a lesser degree, in other parts of the world (Eswaran et al., 2001).

Similar to the present study, a report from Ethiopia demonstrated that under low input agriculture, nutrients associated with sediments in the runoff were beyond tolerable limit (Girmay et al., 2009). The soil resilience, that is the soil’s ability to restore its quality following a stress or perturbation, also depends on its inherent properties (endogenous factors) as well as climate and management (exogenous factors) (Lal, 1994). Crop residue mulch which applied as a layer at the soil-air interface protects the soil against raindrop impacts, decreases runoff velocity and shearing strength, and reduces runoff amounts and rate. Consequently, residue mulch decreases the risk of accelerated erosion (Wishmeir, 1973). Because mulch has favourable effects on soil quality and resilience, and also moderate soil temperature and moisture regimes, mulching has beneficial effects on crop growth and yield (Geiger et al., 1992). Crop residue requirements for erosion control depend on a multitude of soil factors, including texture, structure, and slope (Unger, 1985).

The objective of the study was to evaluate the effects of three mulches, namely coconut leaves, banana leaves and vetiver plants, at three different rates, on soil erosion control, runoff control, soil nutrient retention, and particle size distribution. All the three plant species studied as mulches are available readily and in large quantities in the study region, and are easily identifiable by the local people. No scientific studies have been carried out in Rodrigues on the use and effects of mulching, and this paper reports the first study of its kind. The importance of mulching is particularly relevant in the island of Rodrigues, given the observed impacts of climate variability and climate change, such as increasing temperatures, long periods of drought, short periods of torrential rains (MMS, 2010, Pers. Comm.), which are exacerbating the soil erosion and loss of fertile topsoil that are consequences of the sloping terrain of the island.

2 Research methodology

2.1 Site description

This work was conducted in the island of Rodrigues (lat. 19°43’ and lon. 63°25’), spreading over two seasons in the valley of Nassola. The site is 335 metres above sea level, on a slope of about 8% towards the north. The soil is located on basaltic bedrock and is of the Low Humic Latosol (USDA-Tropeptic Haplustox and FAO-Humic Nitosol). The soil is slightly acidic. Crop production is usually of low external input; maize and beans are grown predominantly. The experimental plots belonged to one of the farmers in the village of Nassola and the plots were used as a demonstration plot for other farmers of the Nassola valley. Although the plot was under fallow for two seasons, there was clear evidence of serious erosion, as a rainwater harvesting reservoir located down the slope showed heavy siltation.

The meteorological data for the period of the two-year study was as follows: annual precipitation 157.2 mm; mean temperature 25.6°C with a max temperature of 33°C; relative humidity 78%; (Mauritius Meteorological Service, Pers. Comm., 2010). The trial was conducted for two consecutive seasons in 2009/2010. Results discussed in this paper are mean values of the two seasons.

2.2 Field experimentation and data collection

The experiments investigated the effect of three different mulches, namely banana (Musa sp) leaves, coconut (Cocos nucifera) leaves, and vetiver (Vetiveria zizanoides) grass, at 0 t ha⁻¹, 10 t ha⁻¹, 20 t ha⁻¹ and 40 t ha⁻¹, dry weight. These organic mulches were chosen because they are available in large amounts in the study region and no
economic use of these resources was evident.

The experiment was laid in farmers’ fields in a randomized complete block design with four replications. Before the experiment the site was cleared of vegetation and the existing terraces were reinstated. Each plot was 5 m × 5 m, and the net plot size from which growth and yield attributes was measured was 4 m × 4 m. Plots were separated by a path of 1 m, while blocks were at a distance of 2 m. Soil samples were collected from the plots at depths of 0 – 20 cm during land preparation and at the end of the experiment, and analyzed for physical, chemical, and biological properties using standard procedures (Anderson & Ingram, 1993; Rowell, 1994). Maize seeds were planted in furrows lined with homemade compost at the rate of 20 t ha⁻¹. No chemical fertilizer was applied as the area was under fallow for more than three years. Three seeds were sown per stand with a spacing of 25 cm and the seedlings were thinned to two per stand two weeks after sowing (WAS). Manual weeding was done by hand pulling at 4 and 9 WAS and their dry weight at 70°C were taken from each plots. Plots were watered on alternate days during the morning and evening with 20 litres of water/plot. Sheet metal was embedded to a depth of 15 cm and protruding 15 cm above the soil surface and the boundaries facing along the slope. The design adopted was that described by FAO (1993). Runoff from each plot was measure daily or after every rainfall event. Runoff depth was calculated by dividing total runoff volume collected in the tanks by the plot area. Sediments were calculated after stirring the runoff and taking a known volume (100 ml) and drying it at 105°C. Compost (20 t ha⁻¹) was applied evenly in all the plots and ploughed into a depth of 15 cm.

Soil moisture was measured every two days by tensiometers (pre-calibrated for this soil type) placed in the field. Similarly, soil temperature was measured every alternate day using stainless steel Fisher brand bi-metal dial thermometers, having a stem length of 20.3 cm, gauge diameter of 4.5 cm, and accuracy of 1.0% of dial range at any point of dial.

2.3 Soil and mulch analysis

Percentage of C and N and C/N of the three mulch materials were estimated prior to adding to the soil.

Soil pH, total N, available P, exchangeable K, Ca, Mg, and organic matter were estimated before the start of the experiment. The pH of the soil was determined in situ on a 1:2.5 soil:water ratio with a portable pH meter. Total nitrogen was determined by the Kjeldahl method. Available phosphorus was determined by the Bray method with HCl / NH₄F. Exchangeable K, Ca, and Mg was extracted by 1M ammonium acetate at pH 7 and estimated by flame photometry (Anderson & Ingram, 1993; Rowell, 1994).

Grain yield of maize was measured at maturity at 12 weeks after sowing. Data for each year were subjected to analysis of variance and treatment means were compared using Fisher’s Least Significant Difference (LSD) at 5% level of probability.

3 Results and discussions

3.1 Soil Characteristics

Results of analysis of the soil prior to the experiment are shown in Table 1. The soil is slightly acidic, pH 6.4, probably due to the low rainfall and soil moisture in the area and also because the soil has received no chemical fertilizer and was under fallow. The texture is silty; there were previous signs of erosion as deposition of large amounts of clay was very noticeable down the slope in the water harvesting reservoir. However the fallow seemed to have slowed down the erosion because of the vegetative cover. Nearby cultivated fields showed extensive signs of soil erosion with exposed plant roots and visible bedrock.

The organic matter was 4.15% in the fallow plots which is quite satisfactory. Nearby fields that were under cultivation had a lower organic matter content of 3.75%. This could well be due to the loss of organic matter by decomposition and soil erosion as no soil conservation method was used. C/N was 89.5, which is quite normal for a soil which is not undergoing lot of disturbance.
Table 1  Physical and chemical characteristics of soil in the experimental plots

<table>
<thead>
<tr>
<th>Soil parameter</th>
<th>Values</th>
<th>Soil parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (%)</td>
<td>43.1±1.2</td>
<td>Organic matter (%)</td>
<td>4.15±0.8</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>32.6±1.2</td>
<td>Total N (%)</td>
<td>0.026±0.002</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>24.3±0.8</td>
<td>Av. P (mg kg⁻¹)</td>
<td>6.23±0.51</td>
</tr>
<tr>
<td>Bulk density (×10³ kg m⁻³)</td>
<td>1.45±0.5</td>
<td>Exch. K (mg kg⁻¹)</td>
<td>96±4.3</td>
</tr>
<tr>
<td>EC (ds m⁻¹)</td>
<td>1.36±0.3</td>
<td>Exch. Ca (mg kg⁻¹)</td>
<td>150±9.7</td>
</tr>
<tr>
<td>pH</td>
<td>6.4±0.5</td>
<td>Exch. Mg (mg kg⁻¹)</td>
<td>90±5.2</td>
</tr>
</tbody>
</table>

The values of exchangeable K and available P are quite satisfactory, although no chemical fertilizers were applied. The values are due to mineralization of organic matter generally. The soils are quite old and release of nutrients from mineralization of parent materials is expected to be insignificant. The values of Ca and Mg are quite satisfactory and are not expected to adversely influence the results of this experiment. The soil is therefore classified as Low Humic Latosol (LHL), Troptic Halplustox (USDA), Humic Nitosol (FAO/UNESCO).

3.2 Soil Loss

Soil loss was highest in the control (unmulched) plots, equivalent to 8.3 t ha⁻¹ yr⁻¹ as compared to 3.5 t ha⁻¹ yr⁻¹ in the coconut mulched plot at 40 t ha⁻¹, representing a decrease of almost 100%. Furthermore, soil loss due to erosion was more or less dependent on the rate of the mulch applied and also the nature of the mulch. Banana mulch at 10 t ha⁻¹ provided the least erosion mitigation of 5.9 t ha⁻¹ yr⁻¹, whereas coconut mulch at 40 t ha⁻¹ provided the highest erosion control (3.55 t ha⁻¹ yr⁻¹). The mulches provided a reduction in soil losses due to detachment of raindrop impacts, erosive properties of the runoff, as well as transportation of the sediment by raindrop splash and surface runoff (Watson & Laffne, 1988). Mulch cushions the impacts of the raindrops on soil aggregates and offers a mechanical barrier to the runoff, and thereby increases infiltration of water in the soil profile and also acts as a sediment trap.

The difference in the reduction of soil loss from the various mulches is due primarily to the decomposition rate (half-life) of these mulches in the soil. Mulch has a low C:N ratio [e.g., banana leaves decompose at a much faster rate than those having a high C:N ratio (Table 2)]. Furthermore, it is quite probable that soil placement enhances soil microbial activity and soil organic matter, and these enhance soil aggregate stability (Maquibela et al., 2009).

Table 2  C : N ratio of the three mulches tested in the present study

<table>
<thead>
<tr>
<th>Mulch</th>
<th>Carbon (%)</th>
<th>Nitrogen (%)</th>
<th>C/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banana</td>
<td>42.4</td>
<td>2.12</td>
<td>20</td>
</tr>
<tr>
<td>Vetiver</td>
<td>41.6</td>
<td>1.36</td>
<td>30.6</td>
</tr>
<tr>
<td>Coconut</td>
<td>31.05</td>
<td>0.75</td>
<td>41.4</td>
</tr>
</tbody>
</table>

The data in Table 3 stresses the importance of protective soil cover in reducing soil erosion. This demonstrates that all the three mulches, irrespective of nature and rate of application, reduced soil erosion substantially as compared to the control.

Table 3  Sediment loss from mulched and unmulched plots

<table>
<thead>
<tr>
<th>Mulch</th>
<th>0 (t ha⁻¹)</th>
<th>10 (t ha⁻¹)</th>
<th>20 (t ha⁻¹)</th>
<th>40 (t ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>8.3 ± 0.52 a b</td>
<td>5.90 ± 0.24 b</td>
<td>5.60 ± 0.47 b</td>
<td>5.10 ± 0.37 b</td>
</tr>
<tr>
<td>Banana</td>
<td>5.25 ± 0.33 b</td>
<td>4.64 ± 0.39 c</td>
<td>4.10 ± 0.28 c</td>
<td>3.55 ± 0.14 d</td>
</tr>
<tr>
<td>Vetiver</td>
<td>4.00 ± 0.28 c</td>
<td>3.80 ± 0.18 cd</td>
<td>3.55 ± 0.14 d</td>
<td></td>
</tr>
</tbody>
</table>

* Means ± sd followed by the same letter are not significant at P = 5% with LSD.
3.3 Particle size distribution of sediments

Analysis of particle size distribution by Bouyoucous method (Table 4) showed that the sediments from the mulched plots had a higher percentage of the coarse fraction (mixture of coarse and fine sand) rather than the fine fractions (silt and clay). The mulched plots contained less of clay and silt. The clay fraction in the coconut mulch plot was 18% compared to the 25% in the control. This trend was observed in all mulches irrespective of the rate of application. It appears from the result that the mulches have resulted in some degree of sorting by retaining more of the coarse particles than the fine particles. This is partly due to the higher density and higher sedimentation rate of the coarser particles.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Particle size distribution of sediments from mulched and unmulched plots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control (%)</td>
</tr>
<tr>
<td>Sand (2–0.02 mm)</td>
<td>35</td>
</tr>
<tr>
<td>Silt (0.02–0.0002 mm)</td>
<td>40</td>
</tr>
<tr>
<td>Clay (&lt;2μm)</td>
<td>25</td>
</tr>
</tbody>
</table>

3.4 Nutrient losses

Table 5 shows the amount of nitrogen (as ammonium and nitrate), phosphorus (as phosphate) and potassium from the mulched and unmulched plots. Mulches were very effective in retaining nutrients as compared to the unmulched plots. Highest retention was in the coconut mulched plots (40 t ha⁻¹) as compared to the control. Furthermore, the data shows that banana leaves were the least effective and coconut leaves were the most effective irrespective of rates in retention of nutrients. Banana leaves, due to its low C:N ration decompose at a much faster rate and therefore the soil cover was reduced quicker than coconut leaves which had a delayed decomposition.

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Nutrient losses from mulched and unmulched plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulch</td>
<td>Application Rate (t ha⁻¹)</td>
</tr>
<tr>
<td>Control</td>
<td>0.40±0.013a</td>
</tr>
<tr>
<td>Banana</td>
<td>0.30±0.020b</td>
</tr>
<tr>
<td>20</td>
<td>0.25±0.011c</td>
</tr>
<tr>
<td>40</td>
<td>0.23±0.012c</td>
</tr>
<tr>
<td>Vetiver</td>
<td>0.30±0.020b</td>
</tr>
<tr>
<td>20</td>
<td>0.28±0.012bc</td>
</tr>
<tr>
<td>40</td>
<td>0.22±0.010c</td>
</tr>
<tr>
<td>Coconut</td>
<td>0.20±0.014e</td>
</tr>
<tr>
<td>20</td>
<td>0.17±0.015d</td>
</tr>
<tr>
<td>40</td>
<td>0.15±0.013d</td>
</tr>
</tbody>
</table>

* Means±sd followed by the same letter are not significant at P=5% with LSD.

3.5 Runoff

The runoff from control plots as well as mulched plots is shown in Table 6. It is clearly seen that all the mulches drastically reduced runoff. Highest mitigation of 75% was observed in the 40 t ha⁻¹ coconut mulch and lowest in the 10 t ha⁻¹ banana leaves (25%). All the mulches offered mechanical barriers to the water flow and improved infiltration. Such substantial reduction in runoff is attributable to increased infiltration due to water flow retention, and also dissipation of raindrop energy, and prevention of surface sealing. Similar findings have been reported by other investigators (Bhatt & Khera, 2006). Furthermore, increased organic matter, brought about by the decomposition of the mulches, is another possible explanation for the reduction in runoff. However such high reduction in
runoff may not prevail for a long time as the water will slowly cause soil crusting and hence infiltration will reduce with time.

<table>
<thead>
<tr>
<th>Table 6</th>
<th>Runoff (mm) from mulched and unmulched plots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 (t ha⁻¹)</td>
</tr>
<tr>
<td>Control</td>
<td>40±2.4 A *</td>
</tr>
<tr>
<td>Banana</td>
<td>30±3.1 aB</td>
</tr>
<tr>
<td>Vetiver</td>
<td>22 ±1.9 aC</td>
</tr>
<tr>
<td>Coconut</td>
<td>18±1.3 aD</td>
</tr>
</tbody>
</table>

* Means±sd followed by the same capital letter down a column, and same small letter across a row, are not significantly different at 5% using LSD.

4 Conclusions

The work clearly shows the beneficial effects of the three mulches investigated. Soil loss and nutrient loss with runoff were all drastically reduced; the mechanism by which these reductions are brought about are mainly mechanical barriers to raindrops on soil aggregates, increased water infiltration, activation of soil microbial activity. The experiment conducted on farmers fields acted as a demonstration plot for all farmers in Nassola valley. Since the farmers were involved in the experiment right from its inception, it had wide ownership and the technology was widely adopted by the farmers. A booklet on the beneficial effects of mulching was distributed freely to all farmers.

Acknowledgements

The author thanks the EU-DCP for having funded this work and to all the farmers of Nassola Valley, Rodrigues, who participated actively and enthusiastically in the project.

References


Hydrological cycle research by D & $^{18}$O tracing in small watershed in the loess hilly region

Xu Xuexuan$^1$, Zhao Jiaona$^2$, and Zhang Xiaoni$^3$

Abstract

The objective of this study was to determine the mechanisms of the hydrologic cycle in the loess area in China. Sixty eight water samples from precipitation, soil water of the 0~4 m layer, surface water in the valley, ground water (spring and well) were collected and the Deuterium (D) and Oxygen $-18$ ($^{18}$O) of these water samples were analyzed to interpret the relationship among those waters in the watershed in the loess hilly region during 2005~2009. The results show that; the D & $^{18}$O of precipitation in Yangou was consistent with that of Xi’an, apparently the north migration of water vapor in Xi’an; according to the correlations among the differential waters in D & $^{18}$O, confirmed that precipitation recharge could account for most of the sources of valley flow, with part of the recharge water going to soil water recharge. The D & $^{18}$O of groundwater were very close to that of precipitation, likely the soil preferential flow was dominant in groundwater recharge although the infiltration had a certain lag. Under the influence of rainfall and evaporation, the response of the soil moisture profile, and its D & $^{18}$O profile were different. The soil moisture had the strong influenced layer in the 0~60 cm range, a weak impacted layer in 60~160 cm, and a stable layer below 160 cm. It was shown that the soil evaporation depth could be up to 160 cm because the D & $^{18}$O changed in that depth. The study could increase our understanding of the magnitude and pattern of the hydrologic cycle, which should improve water resources management in the watershed scale.

Key Words: Hilly area in the Loess Plateau, Precipitation, Groundwater, Soil water, $\delta$D & $\delta^{18}$O

1 Introduction

In the process of hydrological cycle in precipitation, surface water, groundwater, soil water and plant water, Fractionation Effect caused the different contents of isotopes in those water bodies. According to the different contents of isotopes in different water bodies, the way and the amount of conversion could be researched (Zhang et al., 2006). In 1961, Craig, based on the statistics on isotopes of the global fresh water, firstly set up the Global Meteoric Water Line, called GMWL; $\delta D = 8\delta^{18}O + 10$ (Tian & Duan, 2007). In different regions, compared with Global Meteoric Water Line, the measured Meteoric Water Line had different degrees of deviation in the slope and the intercept, which reflected the origins of precipitation clouds in different areas, as well as, the difference in precipitation clouds of unbalanced levels of gas and liquid isotopes fractionation under the change of environmental

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conditions during migration (Yin et al., 2001). In order to quantize and compare these differences, Dansgaard (1964) defined the Surplus of Deuterium, $d = 8\delta D - 88^{18}O$, and the average value of $d$ in the global precipitation was 10. From then on, hydrogen and oxygen stable isotopes were widely used in researching Hydrological Cycle. With the majority of studies on precipitation (Zheng et al., 1983), rainfall infiltration (Wang & Liao, 2007; Tang & Feng, 2001), rainfall runoff response (Gu, 1995; 1992), the supply of groundwater (O’Driscol et al., 2005; Xu & Chen, 2010), and the conversion in different water bodies (Gu, 1992; O’Driscol et al., 2005; Revesz & Woods, 1990) at home and abroad, it was proven that the method of hydrogen and oxygen isotopes was feasible. From Xi’an to Yan’an in the Loess Plateau in China, the amount of annual precipitation reduced rapidly from 650 mm to 520 mm and the evaporation was intensive, which enhanced Fractionation Effect among vapor migration and facilitated Environmental Isotope Method to research Hydrological Cycle in this area.

In this research, Egg Mao Gully in Yangou in loess hilly region was selected as the object. Samples including rainfalls, soil water, surface water of valley, ground water (spring water, well water) would be collected and the D & $^{18}$O of waters would be analyzed according to the observation materials of precipitation from April to September during 2005 to 2009. The relationship between rainfall, surface water and groundwater also would be argued, which would provide the research on the mechanism of hydrologic cycle in the Loess Plateau with some reference.

2 Research methodology

2.1 The description of research area

The Yangou Watershed in Shaanxi, China, is located between latitudes N36°28′00″ and N36°32′00″ and between longitudes E109°20′00″ and E109°35′00″. The watershed is in the center of the hill-and-gullied loess areas and has a total area of 46.88 km². The main gully is 8.6 km long. The geomorphology is very complicated with many gullies resulting in various types of land utilization, e.g. farming on steep slopes, animal grazing, forestry, etc. The average temperature is 9.8 °C. The average annual precipitation is 546.9 mm, and 70% of the annual precipitation occurs from June to September. And the annual average evaporation on water surface is 1, 100 mm. The testing field was sited mainly in Egg Mao Gully, one gully of Yangou. The area of Egg Mao Gully is 0.32 km² with 0.6 km long and 82 m level difference, which is covered by 1.8 – 100 m-depth loess. According to the data from oil drilling, as the boundary with groundwater basin, the spring water and well water are basically consistent with the surface basin landscape. In this watershed, parent material is loess. Hilly area and gully region are mainly covered by new loess and secondary loess which are the primary cultivated soil. Cultivated loessial soils occupies over 90% in this area, which owns some characteristics, such as, uniform grain composition, a loose and porous structure, vertical joints, the similar properties to the parent material, and without any feature like zonal of soil profile characteristics. Loessal soil is made up of sand clay (42.34% – 58.83%), pink clay (27.96% – 42.48%), and clay (9.36% – 15.18%). In this experiment, the measurement of soil water is based on loessal soil.

2.2 Samples collection and analysis

The distribution of water samples in this experiment is shown in Fig. 1. When the rainfall was over 10 mm in rainy season, all of water in rain gauge should be collected after raining and the water samples were collected, too. According to the weather forecasts, the water samples of well water, spring water and gully water were collected before raining, and after raining samples of those should be collected several times in fixed interval again.

The water samples of soil water: before and after raining, 300 g soil was sampled from different depth of soil horizon profile from 0 to 300 cm in terraces. And soil samples were put into 500 ml plastic bottles and sealed in order to avoid isotopes exchange with outside. Those soil samples were taken into laboratory and Revesz’s Toluene Azetropic Distillation Method was used to extracting soil water. Through distilled indoor, all water samples were collected.

Put 10 – 20 ml water of every sample into the 20 ml glass bottles with seal-packing. Remove the water samples
which were not closely related to rainfall events, and the number of water samples used in this study was 68, including 11 rainfall samples, 23 soil water samples, 10 spring water samples, 8 well water samples and 16 gully water samples. The distilled soil water was sealed in 20 ml glass bottles, too.

3 Analysis and discussion

3.1 Consistency analysis on the $\delta D$ & $\delta^{18}O$ of rainfall between Yangou and Xi’an

The average value of $\delta D$ & $\delta^{18}O$ of precipitation in Yangou and Xi’an (1985–1992), standard deviations and value ranges were shown in Table 1. The data of hydrogen and oxygen isotopes of Xi’an precipitation came from GNIP (Global Network of Isotopes in Precipitation).

In Table 1, the range of $\delta D$ & $\delta^{18}O$ of precipitation in Xi’an had totally contained that in Yangou. The collected rainfall in Yangou almost occurred from June to October. Compared with the structure of rainfall isotopes in Xi’an in the same months during 1985–1992, the range in Yangou was fundamentally the same as that in Xi’an, while the $\delta D$ & $\delta^{18}O$ of precipitation were smaller. This phenomenon showed that precipitation in Yangou derived from the north migration of water vapor of Xi’an, and the $\delta D$ & $\delta^{18}O$ fell down from clouds during migration, which caused that the heavy isotopes of precipitation in Yangou was less than that in Xi’an. This analysis tallyed with the fact that the water vapor of Yangou came from Xi’an.

When the precipitation influenced by intense evaporation emerged the dynamic Fractionation Effect, the surplus of Deuterium was decreasing (Aragü et al., 1998; Zhang & Wu, 2009). According to the definition of Surplus of Deuterium (Dansgaard, 1964), the range of surplus of Deuterium of precipitation in Yangou during June–October was $-8.33$–$14.63$, and the average value was $5.91$ which was less than that in Xi’an. This phenomenon illustrated there was an intense evaporation in Yangou during June–October.

3.2 The relationship and the characteristics of $D$ and $^{18}O$ in different waters

What was shown in Table 1 was the heavy isotopes eigenvalues in those five water bodies. Because of the differences caused by evaporation fractionation, there was a significant difference in the contents of heavy isotopes in those water bodies, and the contents of $\delta D$ & $\delta^{18}O$ from low to high were rainfall, spring water and well water, gully water, and soil water. There was a little difference in the range of $\delta D$ & $\delta^{18}O$ of spring water and well water, which stated clearly that they had the similar recharge sources. The average value was close to those of rainfall in Yangou, and it indicated that the precipitation was the dominant direct recharge of groundwater and the infiltration was not affected by the absorbing exchange between rain and soil. That is to say, the recharge of soil preferential flow was dominant. The value range of gully water was similar to that in rainfall, which showed the hydraulic rela-
tionship between rainfall and gully water was intimate but less close than that of spring water and well water. The value range of gully, spring and well water were approximate, which indicated that there were some recharging relationships between surface water and groundwater. The δD & δ18O of gully water was a little more than that of well water and spring water, which may resulted from the recharge of interflow that enriched heavy isotopes.

According to the second observation data of rainfall and weighting water, the average values of δD & δ18O of rainfall in Yangou were −70. 37‰ and −9. 53‰ respectively.

### Table 1

<table>
<thead>
<tr>
<th>Water body</th>
<th>δD (%)</th>
<th>δ18O (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>Soil water</td>
<td>−23.42</td>
<td>24.68</td>
</tr>
<tr>
<td>Gully water</td>
<td>−64.74</td>
<td>15.12</td>
</tr>
<tr>
<td>Spring water</td>
<td>−68.26</td>
<td>2.94</td>
</tr>
<tr>
<td>Well water</td>
<td>−68.58</td>
<td>2.75</td>
</tr>
<tr>
<td>Rainfall</td>
<td>−70.37</td>
<td>24.76</td>
</tr>
<tr>
<td>Average rainfall of Xi’an</td>
<td>−48.29</td>
<td>24.76</td>
</tr>
<tr>
<td>Rainfall of Xi’an from Jun. –Oct.</td>
<td>−51.34</td>
<td>23.36</td>
</tr>
</tbody>
</table>

### 3.3 The recharge of soil water after rainfall

Fig. 2 showed the heavy isotopic composition and soil water content in different depths (0−300 cm) of terraces from 28th May, 2009 to 12th June, 2009. There was 22. 7 mm rainfall on 27th May,2009, and the δD & δ18O of rainfall were −61. 93‰ and −7. 91‰; and there was 12. 2 mm rainfall on 7th June, 2009.

As shown in Fig. 2, soil water content of surface soil (0−10 cm) was all lower, while the δD & δ18O of soil water were higher. It indicated that the surface soil evaporation was intensive and that the heavy isotopes were enriched quickly in soil water by evaporation fractionation. In the depth of 20 cm, the heavy isotopes in soil water were depleted apparently because the evaporation fractionation decreased after the precipitation recharge, and the water content reached the peak on 28th May. In the depth of 30 cm, the δD & δ18O increased and there was a high value of soil water content. Some studies (Zhang et al. 2003; Gong et al. 2005) showed that the ploughpan of cultivated loessial soils was about 20−40 cm underground, having poor water permeability and the declining infiltration rate. So when the rainfall infiltrated to this layer (about 30 cm), continued infiltration rate become slower, which led to water retention, and then more water joined the water from upper layers, so the δD & δ18O raised. The infiltration rate decreased with the increasing depth, which caused that there was a declining trend in soil water content and intensity of evaporation in 30−60 cm, and the δD & δ18O in 30−50 cm also showed a decreasing trend. In Fig. 2(c), the soil water contents on 2 different days in 60 cm were similar, and it indicated that the rainfall on 27th had not infiltrated to 60 cm before measuring on 28th May. Secondly, there was a decrease in soil moisture in 60−160 cm in the later period, while the δD & δ18O raised more obviously than before [Fig. 2(a) and Fig. 2(b)]. And it was believed that this range (60−160 cm) was the weak evaporation layer and the effect of evaporation fractionation was clearer because this layer had less water. The δD & δ18O in 160−300 cm had little change in each of two moments, and there was also no change in soil moisture, so this layer may be the stable layer.

In the profiles of δD and δ18O [Fig. 2(a) and Fig. 2(b)], the changed trend of the δD & δ18O of soil water in different depth among 0−50 cm was no difference between 28th May and 12th June. The curve of 12th June was the right movement of the curve of 28th May, which showed that the δD & δ18O of soil water were enriched obviously because of the evaporative fractionation. In Fig. 2(c), the soil moisture in 0−50 cm on 12th June was much less than that on 28th May. And the heavy isotopes of soil water were enriched under the supporting of evaporative fractionation. In the depth of 60−160 cm, soil moisture was less than that on 8th May. At the same time, Fig. 2(a) and Fig. 2(b) showed that the δD & δ18O were enriched. Below 160 cm, soil moisture, the δD & δ18O all remained
stable during measuring. It inferred that the precipitation recharge and the evaporation occurred in the depth of \(0-60\) cm, \(60-160\) cm was the weak evaporation layer, and the stable layer was below \(160\) cm. In term of the \(\delta D\) & \(\delta^{18}O\) of soil water, the soil layer could be divided into two parts; the affected layer (\(0-160\) cm) and the weak affected layer (below \(160\) cm).

Fig. 2 The \(\delta D\) & \(\delta^{18}O\) profiles of soil water and soil water content profile in 2009

3.4 The precipitation recharge of groundwater

In Fig. 3, water sampling points of groundwater were near to the LMWL, which indicated they were from atmospheric precipitation. However, those points deviated from the LMWL to some degree, and most of them were located in the bottom right of the LMWL. It showed that the rainfall was evaporating and fractionating in the process of precipitation recharge. The changed trend of composition of stable hydrogen and oxygen isotopes in groundwater (spring water and well water) could be fitting with a straight line; \(\delta D = 4.25 \delta^{18}O - 31.073\) and \(R^2 = 0.5402\). That was the evaporation line of groundwater. Its slope and intercept were all smaller than those of the LMWL, which reflected the climate characteristics of Yangou, the small rainfall and strong evaporation. The water sample

Fig. 3 Relationships between \(\delta D\) & \(\delta^{18}O\) for precipitation, surface water and groundwater in Yangou Watershed
points near to the intersection of the evaporation line and the LMWL formed the characteristics of hydrogen and oxygen isotopes of rainfall at the beginning of groundwater formation (Zhai et al., 2011). In the intersection, the δD & δ18O were -73.32‰ and -9.94‰ respectively, which were closer to that of the rain in Yangou (about -70.37‰ and -9.53‰). And it instructed further that the recharges of spring water and well water were closely related to rainfall from June to October in Yangou. The ranges of spring water and well water were small and there was a significant difference while compared with the rainfall in same period. It showed that although the groundwater accepted rainfall, this recharge was not a rapid process and certainly lagging to some extent. The δD & δ18O of well water on 16th, 20th and 25th Aug. decreased slightly but increased on 1st Sep., which indicated well water received recharge by some depleted water bodies during 16th to 25th. Aug. At the same time and before, the rainfall on 24th July was more and the heavy isotopes were depleted to those on 20th and 25th Aug. So it was deduced that spring water was recharged by rainfall in 24th July during 16th to 20th Aug. and this retardation time was almost 23 – 27 d. Dang et al. (2011) had researched the relationship between rainfall and spring flow in Yangou and found that the retardation time of spring water respond to rainfall was about 22 – 30 d., which was consistent with the result in this article. In Table 2., the δD & δ18O of well water on 29th July and rainfall on 24th July was similar to those of well water on 8th Sep. and rainfall on 3rd Sep. The intervals were all 5 d. Dang et al. (2011) also found that the time that the well water respond to rainfall was approximately 7 – 10 d., which was also consistent. But because of the shortage of observation data of well water, the specific time that well water respond to rainfall need further investigation.

| Table 2 | Characteristics of δD and δ18O of precipitation, surface water and groundwater in 2007 |
|----------|-----------------------------------------------|-----------------------|------------------------|--------------------------|
|          | Rainfall (mm) | δD (%) | δ18O (%) | Gully water | Date | δD (%) | δ18O (%) | Spring water | Date | δD (%) | δ18O (%) | Well water | Date | δD (%) | δ18O (%) |
|          |                |        |          |             |       |        |          |             |       |        |          |            |       |        |          |
| 7–24     | 83.66          | -79.63 | -10.89   | 7–26        | -77.27 | -10.51 |         |      |         |          |            |       |        |          |
| 7–27     | 84.84          | -108.07 | -14.75  | 7–28        | -90.75 | -11.91 |         |      |         |          |            |       |        |          |
| 7–29     | 2.3            |         |          | 7–29        | -98.67 | -13.80 |         |      |         |          |            |       |        |          |
| 8–9      | 3.19           |         |          | 8–8         | -62.17 | -7.95  |         |      |         |          |            |       |        |          |
| 8–29     | 40.06          |         |          | 8–19        | -63.41 | -7.93  |         |      |         |          |            |       |        |          |
| 8–31     | 11.28          | -104.05 | -14.30  | 8–26        | -69.09 | -9.31  |         |      |         |          |            |       |        |          |
| 9–1      | 13.56          |         |          | 9–1         | -68.23 | -9.28  |         |      |         |          |            |       |        |          |
| 9–2      | 18.04          |         |          |             |         |        |         |      |         |          |            |       |        |          |
| 9–3      | 5.74           | -78.37 | -11.63   |             |         |        |         |      |         |          |            |       |        |          |
| 9–6      | 20.70          | -58.81 | -8.81    | 9–8         | -84.06 | -11.08 |         |      |         |          |            |       |        |          |
| 9–13     | 1.83           |         |          |             |         |        |         |      |         |          |            |       |        |          |

3.5 The precipitation recharge of surface water

In Fig. 3, water sampling points of groundwater were near to the LMWL, which indicated they were almost from atmospheric precipitation. Set up the linear relation between δD & δ18O of gully water, and there was an evaporation line of surface water: δD = 6.4509818O - 10.899 and R² = 0.9797. Its slope and intercept (-2.8909) were lower than those of the LMWL, which illustrated that rainfall was also evaporating and fractionating when recharging surface water. The δD & δ18O of gully water on 26th July, 2007 were similar to those of rainfall on 24th July (Table 2.), and it showed that most of the gully water on 26th July came from the rainfall on 24th July. Under the influence of rainfall (84.84 mm) which was depleted with heavy isotopes on 27th July, the δD & δ18O of gully water on 28th and 29th were decreasing closely to those of rainfall on 27th. It stated that, at the same time, the effect on valley flow by rainfall on 24th reduced slightly. Instead, the effect by rainfall on 27th increased. It showed that the valley flow was influenced dominantly by rainfall during this period. Dang et al. (2011) also found that there was an excellent response between surface runoff and rainfall in Yangou.
4 Results

Analyzing the characteristics of δD & δ18O of rainfall in Yangou and Xi’an, it showed that the moisture source in Yangou was as the same as that in Xi’an and derived from the north migration water vapor of Xi’an. Under the influence of evaporating during migrating, the slope and intercept of the LMWL in Yangou were all lower than those in Xi’an.

After analyzing the characteristics of heavy isotopes in those five water bodies, it was found that the direct recharge of groundwater and surface water were affected dominantly by the rainfall in Yangou, with little soil water under evaporation and fractionation. That was to say, soil preferential flow was leading the recharge of groundwater. With the recharge by some soil water, the gully water was almost from rainfall, too.

There was a certain lag in the recharge of precipitation to groundwater, and the response time from spring water and well water to rainfall was about 23–27 d and 5–7 d, which was influenced by the depth of groundwater level.

The migration of rainfall on the soil profile could be divided into three parts; the strong influenced layer (0–60 cm), the weak influenced layer (60–160 cm), and the stable layer (below 160 cm). And the δD & δ18O on soil profile could be divided into two parts; the fractionation layer (0–160 cm) and non-fractionation layer (below 160 cm).

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References


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