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*Founders & Editors in Chief*
M.A. M.A. Ruth Schaldach
Prof. Dr.–Ing. Ralf Otterpohl

*Co-Editors*
Tina Carmesin
M.Sc. Isidora Vrbavac

*Layout & Design*
M.Sc. Isidora Vrbavac

*Authors*
M.Sc. Stefan Hügel
M.Sc. Giovanni Timillero
M.Sc. Ruth Schaldach

*Address*
Institute of Wastewater Management
and Water Protection
Eißendorfer Straße 42
21073 Hamburg

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# From the Editors

*Preface by Ruth Schaldach*

The bimonthly published RUVIVAL Publication Series is part of the open source learning project RUVIVAL. The project RUVIVAL is dedicated to building a knowledge base concerned with restoring degraded areas and creating new, not just inhabitable, but liveable spaces. Each contribution in this publication is connected to further interactive multimedia material, which can be reached under www.ruvival.de.

Each volume in this publication series consists of multiple literature review papers, which are centred on a specific overarching topic, which is a cornerstone of sustainable rural development. The research approach draws a systematic and interdisciplinary connection between water, nutrition, climate, energy. Measures which enable sustainable use of land resources and improvement of living conditions are reviewed and new ideas developed with consideration of their different social, political and demographic contexts.

The literature review papers are a collaboration of Master students, PhD students and researchers at the Institute of Wastewater Management and Water Protection (AWW) at Hamburg University of Technology. The work is supervised by at least one senior researcher at the AWW Institute, who is specialising in a related subject. The process entails several feedback rounds and a final presentation of the work, where other researchers of the Institute submit their additional comments. The final version of the literature review is only included in the Publication Series once all feedback has been incorporated and the paper was once again reviewed by the supervising researchers and the Director of the Institute.

We hope that via open access this publication series will reach a broad public and provide a deeper understanding of research fields important for a sustainable rural development and in areas in need of landscape restoration.

*Introduction by Ralf Otterpohl*

All topics of volume 1 are related on several levels. All are part of restoration engineering, a subject that is still not very common. The main goal of my team and me is to encourage all stakeholders to know and to combine those wonderful methods in implementation. Single elements that are usually implemented can be efficient by themselves, but have proven to perform miracles if applied in combination. However, the challenge is to choose and apply all elements in a professional way, to adapt them to the given situation and to consider the system’s many interactions, too. The methods may look simple on the first view, but especially simple and low-cost methods require experience. Few professional failures can be worse than working with villagers, who often put a lot of their hope, money and labour into implementation, and then running them into famine with ill designed systems. Restoration engineering has the potential to raise productivity of eroded areas hundredfold. Income, excellent nutrition and well-being for family farmers and their children, in my point of view, should be the foundation for self-promoting solutions.

Agroforestry is a wonderful, multi-faceted system that should always be considered as a vital part of restoration engineering. Luckily, there is a lot more attention to reforestation today. Including diverse and adapted crop trees is an entry point to agroforestry. With all the options of crop trees, often even legumes, there can be income generated to create livelihoods for the local population, which is a crucial part of self-funding of projects by villages or farmers co-operatives. Formation of humus, regeneration of the local water cycle and food security go hand in hand. At the same time, fodder can be created in much larger quantities than in overgrazed eroding areas. One tree stands out for all projects in subtropical and tropical regions: Moringa. Many trees of the Moringa family produce abundant food and fodder after only a few weeks. Although not considered a legume, it seems to facilitate the production of large quantities of organic nitrogen for the surrounding soil. Sweet chestnut has an enormous potential for more northern latitudes. It can produce as much carbohydrate as an efficient grain field, but of far better nutritional quality. At the same time, excellent wood is produced and the space can still be used for grazing.

Living Terraces are a wonderful option to combine restoration with fast productivity. Many cultures in areas with seasonal rainfalls have built impressive terraces with stones. With the abundance of rocks it surely is feasible. However, where living terraces are an option, they can be implemented with much less effort. The beauty of the system is that with the construction of swales, much more water will be held back and infiltrated – and through this start-up the terraces can grow. A good choice of trees is crucial, and mixing them into a mutually supportive system with legumes and including the crops that shall grow in the terraces can result in an abundance of food, fodder, rainwater harvesting possibilities and beauty.

Check dams are a sort of first aid measure for eroding areas. The power of water grows really strong further along a catchment, therefore, check dams must be started from the upper parts of the catchment. They should be combined with establishing keyline-trenches in order to direct water from the valleys – where it forms gullies though abundance – into the shoulders, where vegetation is in urgent need of water. Of course, these keyline trenches or swales often can and should be converted to productive living terraces. The choice of suitable places for check dams is highly important and requires systems thinking. A check dam should ideally allow water to be diverted from the gully into a floodplain – sometimes after a second or third step built on the collected eroded soil after the first rains. Keyline trenches are part of an extended and modelled floodplain. Never underestimate the enormous power of rainwater runoff, even if it is hard to imagine in a draught period.

# Inside this volume

# A Review of Agroforestry Practices with an Introduction to the Arba Minch Slope Farming Project

M.Sc. Stefan Hügel

*'Could you have an intensive forest gardening system that yields more per unit area than an allotment? Yes you could. But I would argue that just looking at yields and the maximum you could get out of a piece of land is the wrong way of looking at it. [...]*

*From my perspective, that's the wrong question. The question should be, what can a piece of land provide sustainably, without degrading the environment, without reducing wildlife value dramatically, and obviously still produce useful stuff for people – which is a different question entirely.'*

(Martin Crawford 2011, p. 7)

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***Abstract***

*Agroforestry is the inclusion of trees or other woody perennial plants into agricultural systems, including crop and livestock production. It can also be seen as a combination of agriculture and forestry. While conventional large scale agriculture is mainly concerned with maximising short term yields, agroforestry has the objective of emulating natural ecosystems in order to realise a number of ecosystem services. Those include the protection of soil against erosion and water-logging, minimising evaporation of water from soil and plants by decreasing wind speed, water protection through deeper and more extensive root systems and increased biodiversity. Long term stability and productivity of agroforestry systems surpasses those of conventional monocultures or pasturelands, as they tend to be more resilient, but the establishment of trees on farmland comes with certain challenges. Until the trees start to pay off, several years or even decades might pass. The right combination of trees, crops and animals for the particular climate, soil type and desired outcomes has to be carefully selected, which is often hard to predict in terms of productivity and required management. Trees have the potential to become too dominant and diminish yields of nearby cash crops or pasture grasses. Moreover, agricultural policies still tend to favour large scale conventional farming methods over alternative land management systems by selective provision of subsidies and lack of regulatory framework concerning agroforestry systems in particular.*

***Keywords****: agroforestry, slope farming, erosion control, sustainable agriculture*

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## Introduction

Agroforestry has been defined as an ecological land management system relying on natural resources that diversifies and sustains production by the integration of trees on farmland and agricultural landscapes. Thereby, increased social, economic and environmental benefits for land users at all levels are realised (Alao & Shuaibu 2013).

Agroforestry, therefore, combines elements of agriculture and forestry. It is the practice of including woody perennials into farming systems. Perennial plants are usually defined as plants living longer than two years. Woody perennials include shrubs, trees and vines that develop woody stems and do not die on a yearly basis.

Woody perennials have been used as a source of food before the beginning of agriculture, a practice that has continued ever since. Agroforestry systems stand in contrast to conventional agriculture that relies mainly on annual seed crops like wheat, corn and soy.

Agroforestry has increasingly become a subject of systematic study only in the last 50 years, to find a solution to the alarming rates of soil loss and land degradation on a global scale. One of the main forums where agroforestry research is discussed is the Journal 'Agroforestry Systems', which was started in 1982.

The inclusion of woody perennials in farming systems as part of soil conservation and humus build-up practices has proven to be effective in regards to environmental protection, as well as to provide wide ranging socio-economic benefits.

According to Zomer et al. (2009), farming land is classified as agroforestry, if the tree cover is greater than 10 %, and in this category these different forms of agroforestry systems were identified:

- subsistence livestock silvo-pastoral systems to home gardens
- on-farm timber production
- tree crops of all types integrated with other crops
- biomass plantations within a wide diversity of biophysical conditions and socioecological characteristics.

These systems comprise 46 % of all agricultural lands globally (Zomer et al. 2009).

There are three main classifications of agroforestry systems depending on the components according to Smith (2010):

- silvoarable systems with trees together with crops
- silvopastoral systems with trees together with livestock
- agro-silvopastoral systems with all three components.

In systems with all three components, crops and animals are alternated as part of a crop rotation plan. Otherwise, animals would feed directly on the crops, however, with the right timing, they can be used to clean up harvest residues and prepare and fertilise the soil for the next crop.

Trees in agroforestry systems are usually planted in rows, for better management. In silvoarable systems, the distance between the rows still allows the conventional machinery to pass through and work the crops.

All forms of agroforestry are ultimately inspired by natural ecosystems. They endorse the combined cultivation of mixed species to widen the spectrum of products and increase the system's resilience against an increasingly changing climate, pests and erosion.

## Challenges of Agroforestry

Agroforestry comes with a number of challenges, mainly due to its strong differences to conventional agriculture. From an ecological standpoint, agroforestry is a much more complicated system, compared to monocultures. The same holds true from a legal standpoint, as regulatory framework concerning either agriculture or forestry is for the most part not adjusted to deal with agroforestry systems.

As agroforestry depicts the concurrence of trees and crops or pasture, it is only natural that they will compete for nutrients and water. As a consequence, the roots of tree rows in alley cropping systems often have to be cut every year along the alleys in the upper soil layer so that the crops are not suppressed. Alternatively, Jose et al. (2000) showed that trenches can be dug or plastic sheet root barriers inserted between the tree rows and the crop field. Root barriers have been shown to greatly increase the moisture content in the soil of a maize plot grown in an alley cropping system with oaks and black walnut trees. In the control field without any barriers, the maize plants suffered from water-stress and the yield decreased. It was concluded that the management of the competition between crops and trees is critical for productivity and sustainability of an alley cropping system (Jose et al. 2000).

Competition for light is significant, especially when the trees grow older. A study conducted on a silvopasture system in New Zealand discovered that pasture beneath trees would die off at a canopy closure of 85 % for deciduous trees and 67 % for evergreen trees. Pasture production can be limited by up to 50 % with 100 pine trees per hectare at a tree age of just 11 years (Benavides, Douglas & Osoro 2009).

While ginger was found to increase in yield when grown together with *Paulownia* trees, the same study concluded that the yield of maize and beans grown together with *Paulownia* trees was significantly reduced. The closer maize and beans grew to the trees, the smaller the yield was, clearly indicating competition between crops and trees (Newman et al. 1997).

As can be seen from this example, the success of an agroforestry system heavily depends on the right mix of species. The synergies must outweigh the competition. This depends on many factors, such as climate, soil, age and density of the trees and many more. Planning an agroforestry system and predicting its success can be extremely difficult, due to the complexity of the whole system.

Additional equipment for managing trees, like trimming the branches and cutting the roots of adjacent crops will be needed as well. Furthermore, as the range of products gets extended by tree crops, biomass, timber, etc., the management of harvesting, processing and marketing will increase in complexity as well. A monoculture on the other hand is a much simpler system with easier overall management.

The practice of growing leguminous trees and using their foliage as fertiliser is widespread in the tropics, but even though it is effective in providing mainly nitrogen to the crops, it cannot compete with mineral fertilisers in terms of short-time crop yield increase. It was shown that the application of *Leucaena* foliage to maize plants more than doubled the yield from 1.3 t/ha to 2.7 t/ha, compared to non-fertilised maize. However, the application of mineral fertiliser almost tripled the yield to 3.7 t/ha (Laquihon & Pagbilao 1985).

Another downside is the slow rate of income return when planting trees, compared to annual crops. Trees take years or even decades before they start bearing fruit or producing enough biomass to be harvested. Ecosystem services provided by trees, like erosion control and attracting beneficial organisms, will take years to come into full effect as well.

Converting a conventional system into an agroforestry system is a capital investment that will most certainly take years before it is redeemed, unlike an annual crop that takes just one season. Exceptions are very fast growing subtropical/tropical trees like *Moringa oleifera* that produce high quality food and fodder with their leaves already a few weeks after seeding.

Lack of regulatory framework concerning agroforestry often poses a disincentive to farmers considering to plant trees on their farmland. The field of responsibility is still largely unclear, neither fully belonging to the ministry of agriculture nor the ministry of forestry.

Certain agricultural policies provide incentives for conventional systems, such as large scale monocultures, which is discouraging farmers from adapting more sustainable methods of farming, including agroforestry (Buttoud 2013).

For instance, in Switzerland agroforestry was popular and widespread until the 1950s. When Swiss authorities decided to run a programme to make way for large scale monocultures by cutting fruit trees, their numbers dropped from 14 million to 2.2 million trees in 2013 (Sereke et al. 2016). Even programmes that specifically target agroforestry development can discourage small scale farmers from planting trees on their fields by only supporting large scale operations. For example, the Uplands Agroforestry Programme in the Philippines (UAfP) granted public support for those that planted more than 50 ha, while the majority of agroforestry managers are operating small scale systems (Buttoud 2013).

The Polish Ministry for Agriculture and Rural Development introduced agri-environmental schemes for organic orchards in 2009. This scheme was paying 400 € per hectare for orchards with one species, but only 200 € for mixed species orchards (Europarc Federation 2011).

In Estonia, 25 % of agricultural land does not receive money under the Single Area Payments Scheme (SAPS). Those farmlands include areas under traditional farming methods, with grazing livestock on grasslands with a high share of trees and bushes. Those kinds of farming methods do not comply with the SAPS (Europarc Federation 2011).

Depending on local policies, agricultural subsidies can be based on the surface area of crops only, whereby tree cover is not counted as such. Forest Regulations might even prohibit harvesting, cutting or selling of tree products grown on farmland. Attaining a permit to manage tree products as a farmer might prove difficult because of bureaucracy and legal constraints (Buttoud 2013).

Even though agroforestry is often addressed as a novel way of farming, one must not forget that, as already mentioned in the introduction, almost half of all agricultural land is already considered as agroforestry systems. Adopting agroforestry principles is not so much about learning about something new, but rather unlearning the highly unsustainable practices of high input conventional agro-chemistry that have only become popular over the course of some decades.

## Benefits of Agroforestry

Rather than solely focusing on maximised crop production, agroforestry is aimed at emulating whole ecosystems, including the various functions of different elements. By adopting the principles of natural ecosystems, a multitude of aspects, such as protection of water, soil and air, aesthetics of the landscape, increased biodiversity and many more are incorporated.

The most widely used multipurpose tree in silvopasture systems in the tropics and subtropics is the Lead Tree (*Leucaena leucocephala*). It was shown that by planting rows of the Lead Tree on pastureland, its productivity in terms of live weight gain of the cattle could be increased significantly (Gutteridge & Shelton 1998).

By combining plants that complement each other, rather than compete against each other, the system's productivity can be increased. A silvoarable system where ginger was intercropped with *Paulownia* trees showed a significantly higher yield compared to ginger grown in monocultures. In addition to the increased crop yield, *Paulownia* trees will provide valuable timber. A diversification of marketable products with different harvest times can be achieved by growing different plants together, providing a back-up if one crop fails (Newman, Bennett & Wu 1997).

Farmers in India who started to include eucalyptus and poplar trees in their wheat and barley fields have been shown to increase their net profit by a factor of 2.5 to 3 in 7 years (Agarwal 2015).

A popular practice in agroforestry, especially in the tropics, is the production of green manure. Fast growing leguminous trees are grown directly on agricultural land, either in rows or randomly scattered and lopped frequently for their foliage, the green manure. The leaves are thrown on the soil to enrich it with nutrients, improve its physical properties and fertilise the crops. This practice is also known as ‘chop and drop’. By doing so, the system takes care of its own nitrogen needs, so that mineral fertiliser input can be minimised.

‘Surface-applied *Gliricidia* leaves significantly increased N uptake by maize, and supplied more than 30 % of the total N in the stover and more than 20 % of that in the corn grain, even in the presence of hedgerows. Thus, *Gliricidia* leaf mulch has immense potential to improve productivity in tropical soils.’ (Bah & Rahman 2001, p. 90)

Silvoarable systems can also be used to bridge the time between planting the trees and their first harvest, which can take many years. While the trees are still small, the place between the rows can be used to generate income with annual crops, before the trees get bigger. It is also possible to combine tree rows with shade-loving crops that are grown permanently under the tree canopies. By the incorporation of trees and increasing the biodiversity in farming systems, several ecosystem services are realised, such as regulation of soil, water and air quality, enhancement of biodiversity, pest and disease control and climate change mitigation and adaptation. These ecosystem services arise out of the complex interconnections with the farming system and its environment (Smith 2010).

In silvoarable systems, trees provide shade and shelter, which improves animal-welfare. They also increase infiltration in packed soils and decrease erosion. Trees in general attract birds that serve as biological pest control. Much less of the mineral fertiliser or manure used for the annual crops or pasture is reaching the groundwater as it is taken up by the deeper roots of the trees and thereby most of the nutrients are held within the farming system. The leaf litter of the trees feeds the soil and raises its carbon content.

One study examined the market and non-market ecosystem services value of a combined food and energy agro-ecosystem in Denmark that provided food, fodder and energy simultaneously. The system incorporated food crops, such as barley and wheat, pastureland with clover-grass and several tree species for the biomass production. It was calculated that ecosystem services that included pest control, nitrogen regulation, soil formation, food and fodder production, raw material (biomass) production, carbon accumulation, hydrological flow, aesthetics and pollination produced a total value of US$ 1074/ha. Market ecosystem services (food, fodder and biomass) made 46 % of that number, while the rest came from nonmarket ecosystem services (Porter et al. 2009).

Agroforestry systems have the potential to greatly decrease the rates of erosion and soil degradation, compared to conventional monoculture systems, especially on sloped lands. Studies done on an agroforestry system named Sloping Agricultural Land Technology (SALT) demonstrated a change of soil loss rates over the course of 6 years. By planting different leguminous tree and shrub species along the contour lines and integrating more tree crops, the SALT system reduced soil erosion by a factor of 58, compared to a non SALT system on the same location (Laquihon & Pagbilao 1985).

Another study examined the soil loss rates on steep land plots with different planting systems. Bare fallow land had a soil loss of 557 t/ha/a, a cassava planting had 303 t/ha/a, while a plot with 200 *Grevillea* trees per hectare lost 111 t/ha/a and with additional hedgerows of leguminous shrubs the soil loss was reduced to less than 12.5 t/ha/a (König 1992).

It was demonstrated that an alley cropping system in Nigeria with *Leucaena* rows could reduce runoff by a factor of over 10, compared to a ploughed control plot. Alley cropping with maize resulted in 20 times less soil loss per hectare than a maize monoculture (Lal 1990).

The reasons to opt for agroforestry systems are as unique as the systems themselves. Their success largely depends on the interactions of the individual components, such as the selected species of trees, crops and animals in the context of water, soil and wildlife.

## Implementation of agroforestry practices in the Slope Framing Project

Hamburg University of Technology and Arba Minch University are developing the Slope Farming System in Arba Minch as a means to combat erosion and make extremely degraded land productive again using agroforestry practices. Living terraces will be built on slopes to control erosion and reduce water runoff. Those terraces will consist of very fast growing trees, like *Moringa oleifera*, and leguminous multi-purpose trees, like *Leucaena leucocephala*, *Gliricidia sepium* and *Sesbania grandiflora*. These trees enable the production of food and fodder just after a few months in poor soil and build the basis for diverse intercropping systems and highly productive micro-farms in otherwise degraded unproductive land. At Hamburg University of Technology, we see agroforestry as a highly suitable option for micro-farms to be combined with rainwater harvesting methods, such as swales and irrigation ponds, to store water and rebuild humus in order to increase soil fertility over time and produce food, fodder, timber and other tree products. By emphasising productive trees, the soil is permanently covered and the deep extensive root systems of the trees stabilise it (Smith 1929).

## Conclusion

The adaption of agroforestry still struggles in the presence of conventional large scale farming operations worldwide. Whether an agroforestry system will be more productive depends on a variety of factors that interact in a very complex way. While one combination of crops and trees might work well due to complementary synergies between the different species, another combination might fail due to direct competition for an already scarce resource like water. However, even though the comparison of conventional farming and agroforestry in terms of productivity cannot be finally brought to an end, it is very clear that agroforestry effectively mitigates several pressing global environmental issues. Those include erosion, climate change, biodiversity decline, soil depletion, food security, water protection and pesticide contamination, all of which are at least partly a direct consequence of conventional modern farming techniques. Nevertheless, decision-makers are still diverting subsidies in favour of short-term productivity over sustainability.

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# Living Terraces as Practices in Erosion Prevention and Rainwater Harvesting

M.Sc. Stefan Hügel

*'Most present-day farmers in Guatemala view ancient terraces only as relics. They are mainly concerned with surviving until the next year. Thereby, they view soil erosion as a problem over which they have no control, so it does not concern them. This accounts for many farmers in the world [...]'*

(Dorren & Rey 2004, p. 105)

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***Abstract***

*Living terraces constitute a combination of erosion control measures on slopes. While conventional erosion control structures are proven to significantly reduce rates of erosion, they are often very labour intensive and require tremendous maintenance work in order to remain functional. Small scale farmers in regions with weak economy and a lack of appropriate land use methods are most affected by land degradation and soil erosion. Their soil conditions aggravate the already precarious conditions for farming and make them dependent on fertilisers and pesticides. These conventional farming methods intensify the already worrisome soil conditions and intensify erosion. Long term investments are difficult to carry out for small scale farmers. Switching to organic farming and labour intense erosion control measures is often avoided and most low income farmers do not even consider erosion control methods, simply because they are more concerned with their daily survival. Living terraces have the aim of providing effective erosion control and soil building with minimal labour input and maintenance work. At the same time they provide a source of income in form of livestock fodder and green manure after only a few months. This is made possible by using fast growing and draught resistant food and fodder trees like Moringa oleifera. They create a living structure with vertical and horizontal elements that holds back runoff solids and accumulates them to form terraces over time and hold them in place even in heavy rainfalls. This type of practice provides a sustainable method of erosion control, which can have a chance of being adopted by local farmers in developing countries.*

***Keywords***: *living terraces,  erosion control, slope farming, rainwater harvesting*

## Introduction

Soil erosion is the most pressing issue concerning global food security. Almost 40 % of the world's farmland is affected by serious degradation. This is directly diminishing agricultural productivity, while the demand of the global population constantly rises. The economic and social effects are most dramatic in developing countries. While two thirds of global erosion are caused by water and the rest by wind, soil gets depleted 16 times faster than it can be replenished (BBC 2000).

Water erosion on slopes has the most devastating effect on soil integrity, as erosion rates in terms of the amount of soil loss per surface area are directly influenced by runoff velocity, which increases with the angle of the slope. Swales, hedgerows and terraces are the conventional erosion control measures that decrease soil loss by minimising runoff velocity. In the following text these methods are briefly discussed, together with their accompanying problems. Finally, a new control method called 'living terraces' is presented.

## Conventional Erosion Control on Slopes

Conventional erosion control generally consists of erosion control structures and cropping techniques that decrease runoff and thereby slow down water erosion. Runoff is rainwater that does not infiltrate into the soil and flows downwards, carrying particulate soil matter with it.

### *Hedgerows*

Hedgerows for erosion control on slopes are aligned along the contour lines, which are the lines that connect points on the terrain of equal height. Preferably leguminous trees or shrubs are chosen that tolerate poor soils and still grow fast. The roots of the trees stabilise the soil and aid in infiltration, whereas the aerial plant parts serve as barriers that slow down runoff velocity. The initial labour input for establishing the hedgerows is significant, but pays off in the future.

Sloping Agricultural Land Technology (SALT) is a popular form of hedgerow erosion control originating from uphill farms in the Philippines. Double-hedgerows of mixed leguminous trees and shrubs are planted along the contour lines. Every 4 - 5 m between the hedgerows conventional crops are grown, which is called alley cropping. The hedgerows are cut frequently and the foliage is distributed on the crop fields to enrich the soil with organic matter. This not only increases soil fertility and production, but also has a beneficial effect on the physical properties of the soil. Increased water absorption and storage capacity of the soil are contributing to decrease runoff volume and velocity. The initial labour input of marking contour lines, seeding the hedgerows and the maintenance work of trimming is significant and a lot higher when compared to the traditional method of corn cultivation. However, after several years, it was observed that the required labour decreased with time, when SALT practices were applied. This was mainly due to the use of green manure from the hedgerows that made weed control in the crop fields much easier. The crop surface area was reduced due to the double hedgerows being placed every 4 – 5 m, which also decreased the workload for the farmers (Laquihon & Pagbilao 1985).

### *Swales*

Swales can be part of a natural landscape or man-made. They are usually constructed as part of rainwater harvesting and soil conservation practices. Swales are simply a depression of land in which runoff accumulates or is slowed down. Artificial swales or contour bunds are popular in permaculture, especially on slopes. They are often constructed along the contour lines of the slope by digging out a ditch and mounting earth right beside it on the down-hill side. The construction can be fortified by integrating stones into the structure and immediately planting trees and shrubs into the mounted earth. Building swales is very labour intensive and needs regular maintenance to guarantee proper functioning (Rowe n.d.).

### *Terraces*

Terraces work quite similar to swales, as they mainly lower the runoff velocity and give the water more time to infiltrate. Terraces, precisely bench terraces, are constructed by reshaping the slope into multiple steps consisting of level or nearly level strips and a steep or vertical downhill face, constructed on the contour line of the slope. The vertical part and the edges are usually fortified with stones. Just like swales, terraces are very efficient in reducing water erosion, but require a significant load of labour for construction, as well as maintenance.

The major challenge of the most common water and soil conservation practices, such as hedgerows, swales and terraces lies in the fact that most farmers are much more interested in short term production than conservation. Dorren & Ray (2004) argue that soil conservation practices must, therefore, result in increased production as soon as possible to provide an incentive to local farmers that is convincing enough to put in the required additional cost and labour for construction, as well as maintenance.

## Living Terraces

The concept of living fences is a combination of several methods with the aim of constructing durable terraces with minimised workload that begin to be productive soon after establishment. First, living fences will be described, as their functionality is quite similar to living terraces.

### *Living Fences*

Living fences are very common in Central America, often as part of grazing operations (Harvey et al. 2005). Instead of conventional fences made out of timber or metal, living fences consist of living trees planted in very dense rows, as close as 10 cm inside the row. Once established, living fences are more durable than timber posts and much cheaper than metal posts. The trees require some time and management until they are fully functional as a living fence, but after they are established, they need almost no work. Living fences are either seeded or, much more commonly, established by hard-wood cuttings, which are cut-off wooden branches stuck into the ground that regrow roots. This is called vegetative propagation and its success rate largely depends on the tree species used.

Most of the species used for living fences are leguminous trees, as they are often able to grow in very depleted soils and still produce good amounts of livestock fodder that can frequently be lopped. At the same time new cuttings for new living fences can be produced.

A good example of a very suitable tree species for living fences is the Chachafruto tree (*Erythrina edulis*). It is extensively used for living fences in Columbia. Very large cuttings of 2.5 m length work well with the Chachafruto tree. They are planted at a distance of 2 m and, after 30 months, barbed wire is attached. One kilometre of this type of fence yields up to 85 t of seedpods that can be used as human food or livestock fodder (Orwa et al. 2009).

### *The Concept of Living Terraces*

Living terraces are quite similar to contour hedgerows, but are constructed with the aim of accumulating soil on the uphill side of the tree row, so that in the long run, bench terraces are formed on their own. This will save a significant workload of manually constructing the terraces. In order for the tree row to retain the soil, a woven structure is built out of long branches that are attached horizontally between the trees, just above the ground. These branches should mainly come from trees that are easily propagated by cuttings, so they will form roots and sprout new branches. Finally, the whole structure, with both vertical and horizontal elements, is made out of living trees. This will greatly increase the stability and durability of the terraces.

The first step in building living terraces is to locate the contour lines of the slope and mark them. Then, trees will be planted along the contour lines, either by seeds or by cuttings at a distance of about 1 m inside the row. Some very suitable trees are the Horseradish Tree (*Moringa oleifera*), the Quick Stick (*Gliricidia sepium*) and the Chachafruto Tree (*Erythrina edulis*). Those three trees can grow on poor soils, can be propagated by cuttings very reliably and produce high amounts of fodder very soon after planting. When the trees have reached 2 - 3 m in height, the top part is cut down and horizontally woven between the remaining tree stumps just above the ground, so that they have contact with the soil and can form roots. This step is repeated, so that the living structure that retains the soil carried by the runoff is growing in height and finally the terraces are formed. The living terraces will be very productive and provide livestock fodder or green manure from very early on. Additionally, cuttings for new living terraces or fences can be easily obtained in large quantities. The maintenance of established living terraces will be limited to replacing dying trees with new ones. The terraces can be used for grazing operations or crop production.

The advantages of living terraces are very similar to living fences. Even though the establishment requires more knowledge and skilled personnel, the whole structure will be more stable and durable, especially the weak points, the downward faces of the terraces. The production of valuable fodder and timber from the trees contributes to the maintenance of living terraces by local people.

### *Living Terraces as part of Rainwater Harvesting practices*

Rainwater harvesting includes several methods of collecting and storing rainwater runoff to mainly use it for irrigation (Boers & Ben-Asher 1982). It is commonly applied in arid or semi-arid regions with intermittent runoff occurrence to make use of local water sources in small-scale operations. The water is stored in underground pits, wells, reservoirs or other structures and can be used as irrigation water, for domestic use after treatment or groundwater recharge. By preventing the rainwater runoff from escaping into gullies and rivers, the water can infiltrate into the soil in a controlled manner without causing water erosion. The soil moisture increases over time, which has a direct beneficial effect on plant growth and improves the physical properties of the soil itself by increasing its water absorption and storage capacity. Especially in arid climates and on steep slopes, this leads to soil that is effectively reducing erosion by soaking up rainwater like a sponge, while increased vegetation growth contributes to the covering and stabilisation of the soil. The Living Terraces can actively contribute to the improvement of rainwater infiltration for storage in the soil or be part of a runoff diverting structure to channel the runoff into storage reservoirs for irrigation during the dry season.

Another important tool in the context of rainwater harvesting is the Keyline design principle (Yeomans 1965). In general, Yeomans (1965) aims to redistribute rainwater runoff by diverting it from the gullies to the ridges of the terrain by constructing several irrigation channels. These channels are not parallel to the contour lines like terraces and have a slight incline, so that the gully runoff moves to the ridges just by gravity. Consequently, erosion in the gullies is reduced and the ridges that typically receive less rainwater get irrigated. Living terraces could be built as a productive support structure for these irrigation channels.

In general, the production of crops on slopes should be shifted towards tree crops as in agroforestry systems (Smith 1929). As a result of this practice, rainwater can better infiltrate into the ground, because most trees have much deeper root systems than annual crops and additionally they provide a better soil cover. By transitioning from modern staple crops like cereal grains to calorie-dense tree crops like chestnuts, nuts and seedpods from several leguminous trees, both food security and soil conservation can be improved at the same time.

## Conclusion

As a future challenge, erosion control, as well as environmental protection in general, must be combined with land management systems in a way that directly benefits the local community on a social and economic level. Sustainable erosion control needs to be embedded in local land management systems. Poverty stricken communities often do not possess the capacity to directly address erosion control not only due to a lack of knowledge, but much more due to a lack of interest, as their main concern is limited to short term production in order to survive. Erosion control measures therefore cannot stand for themselves, but need to be integrated in a wider context, including agricultural practices and water management in order to be both economically viable and sustainable. Implemented in that way, erosion control measures have realistic chances of spreading across rural landscapes through observation and imitation by local farmers, in order to not only protect the soil, but to increase long term productivity as well.

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# A Review of Check Dams as an Erosion Control Practice with a Special Focus on the Loess Plateau, China

M.Sc. Giovanni Timillero & M.A. M.A. Ruth Schaldach

*'Some features on the landscape that were deliberately made by humans look as though they came about naturally, while some that formed naturally appear as though made by people. And, therein lays the mystique of check dams, at least for those of us whose work is principally in archaeological and historical contexts. Viewed in terms of environmental change, there may well be no deliberate human activity that has a greater impact given its minimal input than the construction of check dams. The simple act of dropping an obstacle across a small water course affects land both upstream and downstream.'*

(Doolittle 2011, p. 4)

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***Abstract***

*Check dams, or gully plugs, are structures built across channels to reduce erosion by lowering water speed and accumulating sediments during floods. Check dams are often introduced in degraded areas, where natural or agricultural vegetation cover was lost or not capable of holding the top soil. They represent one of the most used stabilisation measures worldwide, because of their relative simplicity and easy implementation. Check dams can be grouped into two main categories: temporary and permanent structures. Temporary check dams include structures of small-medium size, designed for use of a maximum of ten years. These structures favour the accumulation of sediments and soil moisture, to establish a permanent vegetative cover. Temporary check dams can be removed when their aim of stabilising the gully with vegetation presence is reached. Reversely, permanent check dams are medium-large constructions usually implemented in severely affected sites. They are designed to last many decades and to resist massive flood events and in many cases entire communities benefit from their implementation. Several factors influence the choice of a check dam, such as topography, precipitation intensity, material and financial resources. Advantages of check dams are flexibility, cost efficiency and environmental benefits like groundwater and soil amelioration. However, negative aspects, such as the high risk of failure and the huge maintenance required, must also be considered when deciding to implement a check dam.*

***Keywords****: check dams, gully plugs, erosion control, Loess Plateau*

## Introduction

A check dam, or gully plug is a 'small, temporary or permanent dam constructed across a drainage ditch, swale, or channel to lower the speed of concentrated flows for a certain design range of storm events and to conserve soil moisture' (Stauffer, Carle & Spuhler 2012). Check dams are built in areas hit by intense runoff events, where conventional erosion control techniques are not sufficient. They represent one of the most utilised stabilisation measures worldwide, because of their relative simplicity and easy implementation. However, check dams need to be built at the right places, ideally where water can be directed to suitable areas for groundwater recharge. In addition, work needs to be started in the upstream of a catchment in order to avoid destruction of the structures. Furthermore, suitable land use, humus building and terracing should accompany the 'first aid' of the plugs.

Different articles and manuals on gully check dams were studied and compared. A high degree of accordance between the different sources was found on many features, such as check dam types, technical requirements and construction guidelines. However, discrepancies were noticed with regard to materials, implementation sites and impact of the structure on the local environment. Such variances are in many cases due to the different document sources and areas of reference. It is remarkable that many of the documents are based on, or have as reference, a manual on gully control issued by FAO in 1986. Although several features were progressively updated, many common elements can be recognised in different sections.

## Check dam classification

Several ways to classify different types of check dams are utilised. Check dams can be grouped into two main categories:

1. Temporary check dams indicate structures of small-medium size, having a life span of three to eight years (Geyik 1986; Stauffer, Carle & Spuhler 2012). These structures favour accumulation of sediments and soil moisture, to establish a permanent vegetative cover. Temporary check dams can be removed when their aim of stabilising the gully through vegetation presence is reached. Regular maintenance is needed to avoid failure of the structure and vegetation regrowth must be periodically monitored.
2. Permanent check dams are large constructions, designed to last longer than temporary structures. Such structures are usually built with long-lasting materials, such as cement and steel sheet and do not require particular maintenance. Vegetation presence is not taken into design consideration. These check dams are designed to bear strong flood events and are therefore particularly stable and robust (Pathak, Wani & Sudi 2006).

A distinction based on the utilised materials identifies four main solutions for the realisation of a check dam (Charman & Gallacher 2005; Keller & Sherar 2003; Stauffer, Carle & Spuhler 2012; Zeedyk & Jansens 2006):

1. Brushwood
2. Wire

3. Logs
4. Rocks.

A more accurate description provides additional information on shape and utilisation and includes a higher variety of solutions (Desta & Audgna 2012; Pathak, Wani & Sudi 2006). The following list offers in this sense an overview of various check dam types, with a short description explaining under which conditions each structure should be utilised:

- Single row brushwood check dam: it consists of a row of vertical posts, which acts as a barrier for a layer of brushwood placed upstream it. It is used for low runoff flow (less than 0.5 $m^3/s$). This structure is usually temporary and its stability depends on the quality of the used posts.
- Double row brushwood check dam: this structure can be seen as a stronger version of the single row brushwood check dam, with a brushwood layer packed between two rows of posts. It is thus designed for a slightly higher runoff flow (up to 1 $m^3/s$).
- Loose stone check dam: this check dam is made of small and medium rocks placed across the gully. It is usually utilised for eroded gullies in cultivated and grazing lands.
- Gabion check dam: this structure is particularly tough and long lasting, due to the presence of a steel wire mesh. Gabions are rectangular boxes of galvanised steel, which are filled with small and large stones and subsequently closed and tightened.
- Locally available 'organic' gabion check dam: a more sustainable version of the previous check dam type. Instead of the wire mesh, a box made of organic material, such as bamboo or reed strips, is utilised. In this case a favourable environment for the growth of vegetation is established.
- Masonry check dam: it is made with cement and represents the most expensive of the described structures. It is usually implemented in sites where runoff rates are considerably high and massive floods affect a high number of people.
- Sandbag check dam: this check dam is assembled with bags filled with soil. It is usually implemented in areas where stones are insufficient to build the main body of the structure.

Combinations of the aforementioned check dams are possible, as a consequence of factors like resources and materials availability, conformation of the implementation site and climate situation (Keller & Sherar 2003).

With regard to their final scope, check dams can also be sorted into porous and non-porous structures (Pathak, Wani & Sudi 2006). Porous dams can often be identified with temporary structures, while non-porous check dams correspond to permanent structures. Non-porous dams must bear strong impacts from dynamic and hydrostatic water forces and are normally built with concrete and steel sheet: masonry dams are in this sense an example of permanent non-porous check dams. Porous dams, on the other hand, have the potential to release part of the water forces through the structure, due to the holes present in materials like brushwood, stones and posts: all the check dams built with these materials are classified as temporary structures.

## Construction guidelines

A set of general construction guidelines for check dams could be univocally recognised. Three different sections are hereafter introduced:

1. Practices to avoid
2. Design recommendations
3. Implementation site

### *Practices to avoid*

Some precautions were introduced after experiencing check dam failures due to structural problems (Geyik 1986; Keller & Sherar 2003). Practices to avoid are summed up in the following list:

- Installation of check dams with a straight flat top.
- Check dams without scour protection.
- Structure not keyed to the banks.
- Lack of spillway.
- Poor maintenance and incomplete work.
- Too high structures leading to undermining.
- Poor integration between physical and biological measures.
- Improper spacing between check dams.

### *Design recommendations*

Common guidelines addressed in different manuals (Akvopedia 2016; Charman & Gallacher 2005; Desta & Audgna 2012; Geyik 1986; Keller & Sherar 2003; Pathak, Wani & Sudi 2006; Stauffer, Carle & Spuhler 2012; Zhao et al. 2012) were integrated and as a result, a series of design recommendations valid for all check dam structures is hereafter presented, regardless of used materials and resources:

- The check dam should be firmly keyed to the bed and banks of the gully to provide stability and avoid underflow. A minimum of 0.5 m depth and width across the riverbed and 0.5 m into the lateral banks must be ensured.
- The sides of the check dam must be higher than the middle section, so that water is conveyed over the centre of the dam. In this way, lateral erosion is avoided and the banks are preserved.
- The check dam should not be built in actual watercourses or permanently flowing streams without specific design, because of possible restrictions to fish passage. All water sources must thus be removed.
- The check dam should have a spillway section in the centre, to discharge water and lower the hydrostatic pressure on the structure. The water on the downstream side should be spilled on an apron layer, to prevent undercutting of the structure. The size of the spillway depends on the height and the width of the check dam.
- The check dam should have a scour protection layer on both sides to avoid base erosion and flow under the structure.
- Two consecutive check dams must be spaced at a distance that takes into consideration the gradient of the gully and the expected height of the structures in a way that the higher point of one structure lays at the same height of the lower point of the next one.

### *Implementation site*

Regarding the choice of the location, check dams must be implemented starting at the downstream end section of the affected gully (Pathak, Wani & Sudi 2006). Contrarily, Remaître et al. (2008) claim that check dams are more effective when located in the upper part of the gully catchment. Akvopedia (2016) identifies locations with natural runoff areas and good infiltration capacity as suitable for the construction of a check dam. Other studies agree on the fact that several factors, such as topography of the area, size of the gully, catchment area and runoff rate must be taken into account when evaluating the preferable location for a check dam (Desta & Audgna 2012; Geyik 1986; Keller & Sherar 2003; Stauffer, Carle & Spuhler 2012). In particular, gully network and watershed of the catchment area play a decisive role in the choice of check dam type and location. Such information makes it possible to assess peak runoff and the amount of transported sediments, which are useful indicators for the choice of a proper structure to be implemented.

## Advantages of Check dams

Check dams represent a feasible solution to remediate eroded channels for a multitude of reasons. The aforementioned description identifies the lowering of flow and the conservation of soil moisture as the main goals of a check dam (Stauffer, Carle & Spuhler 2012). However, additional benefits can be recognised, such as:

- Reduction of riverbed gradient and protection of bankside erosion (Pathak et al. 2005).
- Sediments accumulation (ENSAP 2012).
- Groundwater recharge (Akvopedia 2016; Charman & Gallacher 2005).
- Slope stabilisation (Zeedyk & Jansens 2006).

The varieties of materials and resources that can be used make check dams a flexible and suitable solution for different areas and environments. Furthermore, for the majority of the mentioned check dam types, local materials are sufficient to build the entire structure. Hence, cost effective check dams can be implemented in developing countries, where financial resources are limited. Permanent structures, such as masonry check dams and gabion check dams, obviously require higher costs, but they are meant to contribute to the betterment of entire communities (Pathak, Wani & Sudi 2006). An estimation of the average cost of a check dam is reported to be between US$ 200 - 400 for temporary dams and between US$ 1000 - 3000 for permanent dams (Akvopedia 2016). The evaluation is related to their case in India, but can be assumed as a reliable reference for other countries. Variations in cost depend on the materials and the size of the desired check dam. Another relevant advantage of check dams consists in the increase of croplands: accumulated organic sediments act as fertile soil, which replenishes the arid gully bed and can be utilised by farmers (Zhao et al. 2012).

## Disadvantages of Check dams

The biggest disadvantage of check dams is represented by the constant and intense need for maintenance. Maintenance of structural measures must be regularly performed for at least two years after construction completion (Desta & Audgna 2012; Geyik 1986). Moreover, it is required to inspect the check dam after each relevant flood event with regard to sediment accumulation. In some cases sediments should be removed to avoid clogging and overload of the structure. The vegetation established in gully catchment areas must be protected against fire, illegal wood cutting, grazing and encroachment (Pathak, Wani & Sudi 2006). Silt formation upstream of the check dam can lead to a decrease in water infiltration rate in the soil (Stauffer, Carle & Spuhler 2012), influencing the hydrological balance of the area.

Incompleteness of work and improper maintenance can lead to structural damages over time. Furthermore, climate change with local weather extremes has a strong impact on rainy seasons, causing an increase in intense flash floods (OCHA 2016). A single unpredictable heavy storm is sometimes sufficient to cause massive damages to a check dam. Partial collapse and failure of already filled check dams can have dramatic repercussions on the downstream areas, especially in presence of slope gradients (Zhao et al. 2012). After a filled structure fails, huge amounts of accumulated sediments are in fact outright released and transported by the water. In catchments where several structures are present, a knock on effect can take place, resulting in degeneration of the entire environment.

## Case of study: the Loess Plateau

The case of the Loess Plateau of China is representative of potential advantages and disadvantages of a consistent number of check dams in a severely eroded site. The concerned area is considered as one of the most eroded regions of the world (Qiangguo 2002) and check dams in combination with terracing practices have been used for more than 400 years (Zhao et al. 2012). People living in the Loess Plateau have experienced the benefits of check dams in terms of sedimentation capacity, slope stability and increasing croplands, which led to a rise in environmental services and food security for the community (Wang 2011 cited in Zhao et al. 2012). Filled check dams are in fact used as croplands by the farmers, which make use of the fertile and flat sites that are formed upstream of these structures. However, studies (Zhao et al. 2012) revealed that such reservoir surfaces, used as productive farmlands, are currently in severe danger. The filled dams might face failures during strong flood events, causing potentially critical consequences downstream. Such a scenario already happened in 1978, when a large flood provoked the collapse of 47 dams and the complete destruction of 55 (Zhang et al. cited in Zhao et al. 2012). Additional floods led to the collapse of 223 and the demolition of 120 dams in 2001 and the collapse of 70 dams in 2003 (Zhao et al. 2012). Check dams in the study area provide temporary benefits, but do not represent a permanent solution. Moreover, a negative impact of the numerous check dams in the Loess Plateau area on the water cycle of the Yellow River was observed (Zhao et al. 2012). Environmental scientists concluded that human intervention, in form of check dam constructions, was the primary cause of the alteration of the Yellow River streamflow, provoking a decrease in sediment load.

## Conclusion

Check dams are widely used, especially in regions where gully erosion represents a severe issue. Check dams represent a feasible solution against erosion, combining efficiency and adaptability in terms of materials, resources and costs. Indeed, numerous check dam types are available for each specific situation and location. Building must start from the upper reaches of the catchment, constantly followed by terracing. All-year vegetation cover with humus build-up is crucial for a sustainable solution. This can also empower people to make their living on the formerly eroded land and to go beyond first aid. Regular maintenance must be ensured, especially in regions that face intense floods during rainy seasons. Increasing heavy flooding, as a result of climate change, obliges constructors to put greater attention on the post-implementation phase of a check dam, in order to avoid collapses and failures. As can be seen from the case of Loess Plateau, benefits of check dams (fertile surfaces for farmers) can rapidly turn into potential downsides (failures with severe consequences downstream) with a single heavy rainfall. Hence, it is essential to adapt check dams design to changes in context, climate and situation and integrate post-completion supporting structures and continuous maintenance practices.

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