Landscape-level constraints and opportunities for sustainable intensification in smallholder systems in Kamonyi District, Southern Rwanda. Constraints in the form of sloping land requiring terracing for cultivation and opportunities in the form of fertile valley floors enabling more demanding crops and production of fish, poultry and rabbits. Photo credit: A. Sigrun Dahlin

CHAPTER 12

# Landscape-level constraints and opportunities for sustainable intensification in smallholder systems in the tropics

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### Highlights

- A landscape approach can add value to options for sustainable intensification of smallholder farming
- Management practices applied to intensify these systems are often benefitting from and utilizing landscape functions and services
- Landscapes determine the water yield, and its spatial and temporal availability thus affecting irrigation and associated farm-level productivity
- Agriculture is utilizing nutrient flows and stocks in the landscape with the sustainability of the practices being site dependent
- Biological pest control in agriculture is more effective in diversified landscapes

## 1. Introduction

Landscape-level benefits to the functioning of agricultural systems have been taken for granted, until a change of that context made clear what had been lost. In many landscapes a recovery of functions and services proved to be more difficult and take more time than the loss that had occurred. A first step in the direction of recovering such functions is the recognition of how landscapes were traditionally utilized and to acknowledge the services these systems provided, for example, in regulating the provision of surface and ground water, in serving as areas for grazing and fodder collection, in hosting perennial vegetation for firewood, medicinal use, etc., and being biotopes for pollinators and insect pest predators.

A heterogeneous landscape with mixed land uses can serve as a buffer to cope with environmental and economic challenges. Progressive climate change, with increasingly irregular rainfall and extreme weather events, provide an additional rationale to position agricultural intensification firmly into the landscape context, as trees, wetlands and other landscape components surrounding fields can modify the micro- and meso-climate (van Noordwijk et al., 2014*a*).

However, agricultural intensification has reduced the space for the landscape areas surrounding farmland to provide services. Increased pressure on land is widely seen as driving intensification. Land sizes in highly populated areas of Sub-Saharan Africa are possibly approaching the limit of what can sustain a living for small holders (Masters et al., 2013; Hengsdijk et al., 2014). The decrease in farm sizes in Sub-Saharan Africa is expected to continue for some decades, whereas the trend in Asia is towards larger units of land (Masters et al., 2013).

Agricultural intensification through the increased fraction of cropland is frequently associated with loss of landscape heterogeneity (simplification) and the associated loss of landscape related benefits. Intensification in this respect is considered a major driver of global loss of biodiversity and associated ecosystem services (Tilman et al., 2001). At the landscape level, agricultural intensification has been characterized by enlargement of agricultural fields, a reduction in crop and non-crop diversity and shortened crop rotations, leading to a homogenized landscape that is simple in structure and species composition (Margosian et al., 2009).

Ecosystem services such as biological pest control, pollination, and nutrient cycling through dung burial, are delivered by mobile organisms such as insects and birds (Kremen et al., 2007). Landscape simplification due to agricultural intensification has repeatedly been shown to have detrimental effects on ecosystem services delivered by such species (Tscharntke et al., 2005). This is because the abundance and diversity of the mobile species are largely determined by land-use patterns at the landscape scale, while the primary benefits of the ecosystem services they deliver are to the crops or pastures of local farmers. A landscape perspective is therefore critical to effectively manage ecosystem services (e.g., those that relate to movements in the landscape, i.e., 'lateral flows'), which is one prerequisite for turning agricultural intensification into sustainable intensification.

In this chapter we will discuss how on-farm intensification benefits from, utilizes and relies on the surrounding landscape and the services it provides. Our first hypothesis is that a landscape approach can be beneficial for intensification of smallholder farming. Secondly, that most of the management practices applied to intensify these systems today are benefitting from, and utilizing landscape functions and services. Thirdly, that sustainable intensification of smallholder farming cannot be achieved without taking a landscape approach and that the sustainability of the intensified systems needs to be understood, assessed and developed in that context. The objectives of the chapter are, as steps towards the three hypotheses, i) to review landscape benefits to agriculture focusing on water regulation, nutrient cycling and control of insect pests, and ii) to put forward examples illustrating the role and benefits of landscapes for sustainable intensification of smallholder farming.

## 2. Review of landscape benefits to agriculture

Intensification of agricultural systems in the tropics relies on benefits from the surrounding landscape. Some benefits are related to the landscape topography, land cover and hydrology whereas other benefits are dependent on a diversified landscape with a diversity of trees and other perennial plants, and the connectivity between these biological landscape elements. In this section we review some of these landscape benefits and their relation to intensification of on-farm productivity.

## 2.1 Landscapes provide and regulate water for agriculture

Landscapes support important hydrological services such as provision of freshwater, regulation of water quality, partitioning of rainwater into blue (to surface and ground water) and green (to plant and evapotranspiration) water fluxes, and flood water control (Gordon et al., 2010). The supply of these services is influenced by changes in land use and land cover where landscape functions are modified by humans, for example, through deforestation and intensification of crop cultivation. Agricultural intensification may result in land degradation such as soil compaction, erosion and loss of soil organic matter, which negatively affects the soil hydrologic properties such as permeability and water holding capacity (Lal, 1996; Stoate et al., 2001; Recha et al., 2012). Decreased soil permeability reduces water infiltration in favour of erosive quick runoff while reduced water holding capacity reduces water available for crops. Research has shown that agricultural practices that enhance water infiltration and minimize soil disturbance, for example, conservation agriculture, enhance water availability for crops and thus increase crop yield in low rainfall areas (e.g., Ngigi et al., 2006; Makurira et al., 2011). Ecological functions offered by the presence of wetlands, grasslands and forests in the landscape such as groundwater recharge, stream flow regulation (peak runoff attenuation) and water quality regulation by trapping of pollutants, can be lost with agricultural intensification (Lal, 1997; Dixon & Wood, 2003; Calder, 2005). Recha et al. (2012) found that generation of surface runoff increased with time since the conversion of forest to agricultural cropland, implying land degradation, impeded infiltration and decreased water retention.

The structure of a landscape determines the water yield in an ecosystem, both the total (i.e., annual water yield), and the spatial and temporal distribution of available water. The magnitude and the frequency of the dry season stream flow is a very important measure of water availability. Infiltration of rainwater into the ground to recharge aquifers ensures the sustainability of stream flow. The base flow component of stream flow is primarily determined by the groundwater. Reduced infiltration may increase the frequency and the length of low flows (Lal, 1997) which imply less available water for agriculture (irrigation) and other uses for extended periods. Therefore, landscape elements such as wetlands, grasslands and primary forests act as groundwater recharge areas which ensure sustainability of stream flows throughout the year (Lal, 1997; Bruijnzeel, 2004; Farley et al., 2005).

Trees in the landscape modify microclimatic conditions by shading and thus reducing potential evaporation (van Noordwijk et al., 2014*b*). Trees also reduce wind speeds and thus minimize vapour exchange which also lower the evaporation. This minimizes unproductive green water (evaporation) in favour of productive (transpiration) green water (Falkenmark & Rockström, 2004).

Landscapes regulate the quality of surface water bodies. Suspended sediments, nutrients and pesticides from agriculture are major causes of diffuse water pollution (Stoate et al., 2001; Gordon et al., 2010). Field experiments showed that the sediment yield from cultivated land under maize was 64-200% more than that from grassland in the Upper Mara River Basin, Kenya (Defersha & Melesse, 2012). A mosaic of different land uses in predetermined spatial arrangement (e.g., grass strips along the rivers, hedgerows along contours) offers multiple benefits while maintaining the hydrological functions of the landscapes. Grass strips, hedgerows, tree lines, etc., in agricultural landscapes, enhance water infiltration, minimize soil erosion and trap eroded pollutants, while the land is not taken out of agricultural use. For example, Mwangi et al. (2014) found that application of 5 m wide grass strips and 14 km grassed waterways in Sasumua watershed, Kenya, would reduce the sediment load to the Sasumua reservoir by 30% and 23%, respectively.

Multifunctional agricultural systems managed for a number of products and services would improve water management at a landscape level (Gordon et al., 2010; Liniger et al., 2011). Managing upstream and downstream water use is essential to achieve sustainable agricultural production at the landscape scale, as illustrated in a study of two villages in Embu on the slope of Mt. Kenya (Hoang et al., 2014). Good management of resources at field and farm scale will further increase the water and nutrient use efficiency and improve on-farm productivity (Gordon et al., 2010).

## 2.2 Landscape nutrient stocks supply nutrients for farm production

The utilization of landscapes for supporting nutrient supply in agriculture can take place with differing intensities and intentionality. The aim of this section is to illustrate the movement and utilization of nutrients in the landscape. Thus on-farm nutrient cycling and deliberate import of nutrients to farms in the form of chemical or organic fertilizers are outside the scope of this chapter.

Interactions between the landscape and the cultivated fields are fundamental in production systems such as slash and burn cultivation. In these systems, resources are transferred from other landscape elements (virgin or secondary forest, bush, fallows) to agricultural lands. This transfer takes place mostly over time when land is transformed into fields, and nutrients that have accumulated in biomass and soil organic matter during forest or fallow periods are liberated. However, nutrient use efficiency is low since losses are high through volatilisation during burning, and erosion and leaching over the subsequent years (Juo & Manu, 1996; Hölscher et al., 1997).

More permanent cropping systems may also utilize, or be affected by, other landscape components, through spatial transfer of nutrients and organic matter, for instance, by nutrient-rich sediments deposited on periodically inundated river valleys or via fine soil redistribution to low-lying areas of hilly landscapes. Although crop productivity in individual 'receiving' fields may through these transfers be sustained at moderate levels in the medium- to long-term, these systems may not be sustainable at the larger spatial scale because of the disadvantage to other parts of the landscape, and are unviable at higher population densities.

Higher productivity may be achieved through direct and intentional human manipulation to increase flows to the cultivated fields from other landscape components, and to decrease nutrient and organic matter losses from farms. Introducing di-nitrogen ($N_2$) fixing trees, bushes and herbaceous plants onto farms can strongly increase N availability at the field- and landscape-level. Species suitable as livestock fodder (e.g., *Desmodium spp, Mucuna pruriens, Calliandra calothyrsus, Sesbania sesban, Leucaena leucocephala, Faidherbia albida*) may, for example, be planted along boundaries and along contours to stabilise slopes and terraces. These fodder types can increase livestock weight gain and milk production (Gutteridge & Shelton, 1994; Place et al., 2009) compared with a grass-only diet, and the higher N concentration of the produced livestock manure can contribute to enhanced crop productivity (Delve et al., 2001). The $N_2$-fixers may also be used viably as green manures if fitted to the production system in a way that minimises costs and maximises benefits; for example, green manure cut and carry systems (where biomass is produced in one place and transferred to fertilize a crop in another place) are mainly economically viable for production of high-value crops (Jama et al., 2000). Apart from $N_2$-fixation, inflows of nutrients (and organic matter) from other landscape components to cultivated fields are largely via fodder collected or purchased for stalled animals and via grazing animals. For example, van den Bosch et al. (1998) found that purchased feeds and grazing off farm corresponded to an average inflow of 42 kg N/ha/yr on farms in Kakamega, Kenya. In the communal areas of Northeastern Zimbabwe, livestock manure is applied preferably to home-fields. The use of harvest residues from outfields for fodder or supplementary grazing thus leads to net nutrient transfer from the outfields to home-fields, and also from the fields of non-livestock owners to those of livestock owners (Rufino et al., 2011). Corresponding flows arise when livestock graze on grasslands (Rufino et al., 2011), and also when forest litter is collected and used as surface mulch.

Preventing nutrient losses from farms is another aspect of sustainable intensification. Annual nutrient losses through erosion in low-input systems in Sub-Saharan Africa are often in the range of 10 kg N/ha, 2 kg P (phosphorous)/ha, and 6 kg K (potassium)/ha (Stoorvogel & Smaling, 1990). They are thus often larger than fertiliser inputs averaging 6-7 kg NPK/ha/yr (Reij & Smaling, 2008); hence, much could be gained by reducing nutrient losses through erosion control. Also redistribution of nutrients by uptake of deep-rooted plants and trees from deeper soil layers may help retain nutrients in the farming system (Aweto & Iyanda, 2003; Gindaba et al., 2005). However, with the exception of $N_2$-fixation, management options that direct nutrients from the surrounding landscape to arable fields or from deeper soil layers to surface soils imply that nutrients are mined at the source site. While such nutrient transfers are one way to replenish nutrients exported and may also increase the nutrient stocks on-farm, the sustainability of this approach is strongly dependent on the magnitude of the flows, the relative areas of cultivated land and the surrounding landscape, and the capacity of weathering and aerial deposition of nutrients to replenish soil fertility at the source site. Knowledge is lacking in this respect but the net outcomes are bound to be highly site-specific. Nevertheless, taking nutrient flows between crop fields and other components of the landscape into consideration is needed when developing management options for sustainable intensification.

## 2.3 Biological pest control is relying on diversified landscapes

Many pests and their natural enemies are able to disperse over large distances and the damage they cause in a particular field is therefore often strongly affected by the composition and structure of the surrounding landscape. The effects of landscape composition on natural enemies of insect pests have been particularly well studied during recent years. It has repeatedly been shown that the diversity and abundance of natural enemies such as parasitoid wasps, predatory beetles and spiders are higher in diverse landscapes with a comparatively low proportion of crop habitats (studies reviewed by Chaplin-Kramer et al., 2011; Veres et al., 2013). A few studies have also shown that this can result in enhanced pest suppression (Östman et al., 2001; Gardiner et al., 2009; Rusch et al., 2013). A modelling study suggested that landscape simplification in a temperate area would reduce the biological control potential of natural enemies of cereal aphids with about 35% (Jonsson et al., 2014*a*). Similar studies in tropical environments are still scarce (but see Box 12.1).

## Box 12.1

### Landscape management of coffee berry borer to sustain productivity on smallholder farms

Careful landscape management can help to reduce pest infestations. This has been clearly shown by work from Costa Rica and East Africa on coffee berry borer management. The coffee berry borer is currently considered to be the most important insect coffee pest worldwide (Jaramillo et al., 2006). Trees planted and maintained at multiple spatial scales in and around coffee plantations can help reduce coffee berry borer infestations via a range of different mechanisms (Figure 12.1). The abundance of the pest is lower in shaded compared to sun-exposed coffee plantations (Jonsson et al., 2014*b*). This may be due in part to natural enemies such as ants, parasitoids and birds benefiting from and being attracted by trees (Perfecto et al., 1996; Karp et al., 2013). Borers also experience reduced development rates in shaded conditions (Jaramillo et al., 2009), and shade can modify biochemical composition and emission of chemical compounds from coffee berries that make them more difficult to locate for ovipositing borer females (Jaramillo et al., 2013). Landscape composition may also have strong effects on infestation rates. Karp et al. (2013) recently found that forested coffee plantations hosted more predatory birds in Costa Rica than plantations lacking trees, and the damage by coffee berry borers was therefore 50% lower at the forested coffee plantations. This prevented US$75–310/ha/yr in damage. Railsback and Johnson (2013) furthermore suggested that introducing trees within coffee farms will be more effective at increasing predation by birds on coffee berry borers than preserving patches of forest. In contrast, landscapes with a high connectivity between coffee patches will have a higher infestation rate of coffee berry borers than more fragmented coffee landscapes (Avelino et al., 2012).

**Figure 12.1** Trees in and around coffee plantations in Costa Rica have significantly reduced coffee berry borer infestations via different mechanisms, e.g., hosting predators such as birds. Photo credit: Daniel Karp (to whom we are very thankful)

However, even though landscape simplification on average leads to increased pest pressure (Veres et al., 2013), this is not a uniform pattern. Some pests find alternative host plants and other resources in non-crop habitats, and this may counteract the positive effects of enhanced predation pressure. One example are stemborer moths that use native grasses in East Africa as alternative hosts; a high cover of such grasses in the landscape have been shown to enhance stemborer colonization to maize crops (Midega et al., 2014).

In most cases it is not clear exactly how the landscape should best be designed to most effectively reduce pest pressure. This is because we know little about the mechanisms explaining observed correlations with landscape components. For example, it is often assumed that positive effects of landscape complexity on natural enemies are due to the presence of key resources present in the landscapes, such as alternative food or hibernation sites (Tscharntke et al., 2008), but it may also be due to variation in mortality factors induced by habitat disturbances and pesticide application (Jonsson et al., 2012), or by changes in connectivity (Perovic et al., 2010).

One reason for the often poor understanding of the mechanisms underlying landscape effects is that correlations with coarse landscape metrics, such as the proportion of non-crop vegetation, are used. While these metrics may be relevant predictors of biodiversity, they are probably less effective at predicting occurrence of individual pests and key natural enemies that have specific habitat requirements. If more specific landscape metrics motivated by species biology are used in future studies this may not only lead to a better understanding of the drivers of landscape effects, but may also improve the ability to identify landscape parameters that selectively enhance natural enemies while reducing crop pests.

Using a more specific landscape approach has, for example, shown that trees in the landscape can help reduce coffee berry borer abundances through enhanced biological pest control by birds, while highly connected coffee plantations are likely to increase coffee berry borer abundances by facilitating coffee berry borer movement (Box 12.1) (Avelino et al., 2012; Karp et al., 2013; Railsback & Johnson, 2013).

A further reason for using a landscape approach is that the impact of local management measures on biodiversity and ecosystem services often depends on the landscape context. The 'intermediate landscape complexity hypothesis' states that the effect of local management measures such as intercropping should be highest in moderately complex landscapes, but less effective both in highly simplified landscapes dominated by crops and in highly complex landscapes dominated by non-crop habitats (Tscharntke et al., 2012). Empirical support for this hypothesis is mounting, especially for the moderately to highly complex part of the relationship (Schmidt et al., 2005; Haenke et al., 2009) even though such effects are not universal (Winqvist et al., 2011).

As illustrated in this section, many pests and their natural enemies are able to disperse over large distances and thus elements in the surrounding landscape can provide these organisms with resources such as hosts, food, shelter from disturbances, and can enhance or reduce their immigration to crop fields (Tscharntke et al., 2008; Avelino et al., 2012). This clearly highlights the importance of taking the landscape scale into account when designing and testing practices for sustainable pest management.

# 3. Sustainable intensification

Sustainable agricultural intensification focuses on its defined goal of "... producing more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services" (Pretty et al., 2011). In contrast, the process is the emphasis of those putting

Box 12.2

## Forest gardens sustain livelihoods when variable weather hits intensified crop cultivation in Central Vietnam

Globally, Vietnam is among the five countries most affected by sea level rise caused by climate change, as its major rice production areas are close to the sea (Wassmann et al., 2004; Dasgupta et al., 2009). The low coastal area of Central Vietnam is characterized by high poverty, extensive forest and a high dependence on agriculture (Nguyen et al., 2013). Cam My Commune in Ha Tinh Province is an example where dependence on intensified agriculture dominated by paddy rice is jeopardized by strong climate variability and frequent weather hazards. Farmers in Cam My are utilizing resources in the surrounding forest landscape and drawing on the benefits that different trees provide. In addition to home gardens, they have developed 'forest gardens' in the forest area adjacent to the village where they grow a diversity of vegetables and trees (fruit, tea, timber, etc.) for household consumption and the market (Figure 12.2). The 'forest gardens' are established in land designated as forest (belonging to the State Forestry Enterprise). Policy allowing agroforestry in forest land in vulnerable areas is needed and would further improve the life of the farmers in Cam My (Hoang et al., 2014). Such legitimization would officially recognize the benefits of landscape resources (land, trees, etc.) gained by smallholder farmers through their forest garden activities, which are needed to complement their on-farm crop cultivation.

**Figure 12.2** Establishment of forest gardens in Cam My Commune, Central Vietnam, contributes to sustainable livelihoods of local, smallholder farmers. Photo credit: Quan Nguyen

Box 12.3

## Enclosures contribute to sustainable intensification of livestock production in semi-arid West Pokot, Kenya

Population increases and less access to sufficient land for grazing in semi-arid pastoral areas have resulted in reduced per capita livestock assets that underpin traditional pastoralism. This pressure has led to the introduction of cropland, the concentration of livestock, and constrained seasonal migration resulting in overgrazing and land degradation. In West Pokot in northwest Kenya, decades of increased land degradation have been followed by the emergence of community-based institutional change and more sustainable land management practices (Nyberg et al., 2014). These innovative practices, including trees, shrubs and other plants forming live fences and enclosures, have been widely adopted (Figure 12.3). The vegetation does not only provide fodder, fences and other products but also ecosystem services such as reduced erosion, improved water infiltration and carbon sequestration in biomass and the soil. The farmers are now rotating the livestock grazing between paddocks, which are enclosed and interspersed with crop fields. During the same period there has been a change in land tenure towards privatization and individual land use rights.

The above chronosequence of population pressure leading to land degradation, land use change and a subsequent emergence of institutions to support greater land care is a trajectory common to many semi-arid areas and offers excellent scope for research (Triple, 2014). Analysis of the role of population pressure in driving this trajectory reveals that land use changes in West Pokot with lower initial population occurred several decades later than in more densely populated districts such as Machakos, Kenya (Tiffen et al., 1994; Zaal & Oostendorp, 2002; Nyberg et al., 2014).

**Figure 12.3** West Pokot in semi-arid area of Kenya: degraded landscape (left), restored landscaped with enclosures in (centre), livestock grazing in enclosure (right). Photo credits: A. Sigrun Dahlin (left), Gert Nyberg (centre), Ingrid Öborn (right)

forward the concept of 'ecological intensification' as a means to reach sustainable intensification (Bommarco et al., 2013; van Noordwijk & Brussaard, 2014). Garnett and Godfray (2012) broadened the concept to also include nutrition, health and animal welfare aspects. Although the target of sustainable intensification has considerably advanced and broadened the thinking beyond increasing inputs to close yield gaps, the specific steps needed to increase outputs in any given context remain site-specific. The main focus still is very much at the farm level, on scaling up in terms of adoption, value chain development, and market linkages, but there is a lack of awareness of the dependence on the landscape context and the degree to which intensification opportunities and constraints relate to landscape properties, functions and services.

In Section 2 we reviewed some of the landscape benefits to agriculture. The examples we chose for this section highlight the potential of integrated studies to illustrate benefits from landscapes and the necessity to integrate a landscape perspective in research and development activities dealing with agricultural intensification (Box 12.2-12.3). In these examples the distinctions between coping strategies and intensification may be hard to make. The first example is from the low land areas of Central Vietnam where the landscape plays a significant role in making the intensified farming systems more sustainable (Nguyen et al., 2013; Hoang et al., 2014). Development of forest gardens on adjacent land, officially being designated as forest, has provided measures to cope with rainfall variability and extreme weather events that jeopardize crop production and make it possible for the local farmers to buffer household food security and other livelihood needs (Box 12.2). The second experience is from livestock farmers in West Pokot in semi-arid Kenya where enclosures have been established to regulate and intensify the livestock grazing since the increased population and pressure on the land makes it difficult to continue communal grazing and pastoralism (Nyberg et al., 2014; Box 12.3).

# 4. Conclusion

The review of landscape benefits to agriculture brought up several examples and aspects of landscapes functions that can be further utilized for sustainable intensification of agriculture, contributing to increased productivity, food security and income. Examples are measures to improve water regulation, reduce nutrient losses through erosion control and to promote biological pest control. In order to restore lost and degraded functions and services a more complex landscape combining different land uses and landscape components is needed. This is particularly the case for water and pest regulation. However when it comes to nutrient supply, enrichment in one part of the landscape leads to nutrient mining somewhere else, except for nitrogen that can be captured through biological $N_2$-fixation. Trees and shrubs in cultivated landscapes together with grasslands and wetlands are core elements providing and supporting landscape benefits and services required for sustainable agriculture.

However, agricultural intensification, intending to be sustainable, in practice, is concept specific. When this is taken into account, agricultural research and development will be able to contribute to large-scale development impacts (Coe et al., 2014). Policies and policy changes are also required, for example, to enable sustainable farming at the agricultural-forestry interface (Hoang et al., 2014), or linking agriculture and improved on farm-productivity to development of human nutrition and health (Garnett & Godfray, 2012). Sustainable intensification, as discussed here, is not about maximizing short-term production but optimising long-term productivity and a range of environmental and other possible outcomes (Garnett & Godfray, 2012).

This chapter identified opportunities, but also challenges, to find a site-specific landscape approach that is beneficial for sustainable intensification of smallholder farming. A landscape perspective needs to be brought in to further develop the concept and practices of sustainable intensification of smallholder agriculture in the tropics. Management practices applied to intensify these systems can benefit from and utilize landscape functions and services, but they are knowledge intensive and not always easily 'scaled up'.

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