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The effect of rainfall on spatio-temporal variability in cropping systems and duration of crop cover in the Northern Ethiopian Highlands.

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Short running head title: Cropping systems in North Ethiopia

17 **Abstract**

18 In the Northern Ethiopian Highlands ca. 33% of the land is cropland which is mainly
19 cultivated by smallholders who based on indigenous knowledge plan their cropping
20 system on the basis of spatio-temporal variability in rainfall. In order to understand the
21 relationships between rainfall variability and cropping systems, a field campaign was
22 undertaken in the rainy season of 2009 when 118 farmers were interviewed at different
23 locations with different environmental characteristics. Five cropping systems were
24 identified, each having a distinct cropping season length and crop association.
25 Cropping systems with shorter cropping seasons were generally on the valleysides
26 whereas longer cycles occurred in the valley bottoms. The length of cropping season
27 also increased from north-northeast to south-southwest. Crop associations within
28 cropping systems also varied with altitude. Cropping systems changed in responses to
29 variation in annual rainfall. This resulted in shifts of cropping systems at catchment
30 and regional scales, with cropping systems having longer cropping seasons where
31 there was greater annual precipitation. The results were scaled up to the whole region
32 by modelling the spatial distribution of cropping systems at a 8 x 8 km² resolution over
33 the period 1996-2009. The results indicate that indigenous knowledge is important
34 when assessing the impact of climatic variability on agricultural production, and that
35 large inter-annual variability in the duration of crop cover in Northern Ethiopia might
36 be an important, generally overlooked, explanatory factor for explaining previous land
37 degradation cycles.

38

39 **Keywords:** Crop cover, cropping system, indigenous knowledge, Northern Ethiopian
40 Highlands, rainfall variability.

41

42 Introduction

43 About 33% of the Northern Ethiopian Highlands is cropland (Meire *et al.*, 2012; de
44 Mûelenaere *et al.*, 2012). Nearly all this land is cultivated by smallholders who each have
45 about a hectare (Gebremedhin & Swinton, 2003), and produce food following traditional
46 practices for their subsistence or for the local market. As a result of agricultural
47 intensification, total food production has increased significantly over past decades (Nyssen *et*
48 *al.*, 2004; FAO, 2012). However, with a rapid demographic expansion in the second half of
49 the 20th century, the food production per capita increased much less, making a large part of
50 the population dependent on food distribution programs (Segers *et al.*, 2008; van der Veen &
51 Gebrehiwot, 2011). This was especially the case during droughts as the mountainous
52 landscape of Northern Ethiopia does not allow the widespread application of irrigation
53 agriculture (FAO, 2012), thus crop production is primarily rainfed.

54
55 Through centuries of practice and experience, communities have evolved their farming
56 systems in order to optimize production within given climatic and biophysical conditions.
57 The resultant indigenous knowledge on farming practices has been transferred from
58 generation to generation by various ways including oral transmission, repetitive practice and
59 social/community organization (Sillitoe, 1998). Such indigenous knowledge is generally
60 perceived as being very valuable, as it has allowed large communities to exploit
61 environmental resources in a relatively sustainable way over many centuries (e.g., Lagemann,
62 1977; Mortimore *et al.*, 1997; Widgren & Sutton, 2004). It has therefore been advocated that
63 contemporary agricultural developments should take indigenous knowledge into
64 consideration (Dewalt, 1994; Cooper *et al.*, 2008). The importance of indigenous knowledge
65 for farming is especially apparent for poor dryland regions in which cropping is still largely
66 organized according to traditional practices (Devendra & Thomas, 2002; Jarvis *et al.*, 2008).

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The aim of this study was to investigate the relationships between spatio-temporal variability in cropping systems and rainfall in Northern Ethiopia. Emphasis was given to indigenous knowledge for agriculture and the possible impacts of agricultural management on accelerated land degradation.

Materials and methods

Study area

The study area was in the Northern Ethiopian Highlands and covered ca. 10⁴ km² (12°30'–14°10'N / 39°–39°50'E), between 2000 and 3900 m a.s.l. Eight study localities were selected in order to encompass the regional variability in environmental characteristics. From north to south these were Ablo, May Mekdan, May Ba'ati, May Tsimble, Atsela, Ayba, Seytan and Lake Ashenge (Figure 1), in total covering 123 km². Additional observations were made near Atsgeba, Tsabat, Munguda and Korem (Figure 1). The Ablo catchment is underlain by sandstone; May Mekdan and May Tsimble by shale with limestone cliffs and occasionally dolerite at the summits; Atsela, Ayba, Seytan and Lake Ashenge are underlain by volcanics and May Ba'ati by volcanics at higher elevations, while sandstone, limestone and shale dominate the lower elevations.

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Figure 1. Location of the study areas.

The influence of parent material on soil characteristics is important in Ethiopia (Nyssen *et al.*, 2002a; Moeyersons *et al.*, 2006). On the two major lithological units of limestone/shale and basalt, typical soil catenas occur (Nyssen *et al.*, 2008). Along slopes on basalt, Leptosols, Skeletic Cumulic Regosols, Vertic Cambisols and Vertisols are typical. A typical succession in limestone/shale areas is Calcaric Regosols/Cambisols, Cumulicalcaric Regosols and Calcisols. Along these sequences, soil depth generally increases while rock fragment content decreases (Nyssen *et al.*, 2002b; Nyssen *et al.*, 2008). For the sandstone areas, common soils are Luvisols which occur on the plains and plateaus, while Arenosols and Cambisols are on

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the slopes (Kassa Teka *et al.*, 2011). Most soils are young due to active geomorphological processes (Virgo & Munro, 1978).

The movement of the Intertropical Convergence Zone over the Highlands causes three distinct periods in the moisture regime of the region: the dry season (*bega*) from October until February, the spring rainy season (*belg*) from March until May and the summer rainy season (*kiremt*) from June until September (Figure 2; Cheung *et al.*, 2008). In the *belg* season, monthly rainfall is generally low and highly unreliable (Nyssen *et al.*, 2005). Rains that occur in March-April are very important for crop production in Northern Ethiopia and, if persistent, are called *azmera* rains (Verdin *et al.*, 2005). The *kiremt* season is the main rainy season and accounts for 65 to 95% of the annual precipitation, ending rather abruptly in September (Segele & Lamb, 2005). Average annual precipitation ranges from 500 to 900 mm yr⁻¹ and increases from north-northeast to south-southwest, with important year-to-year variations (Jacob, 2010).

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Figure 2. Ombrothermic diagram of 2006 for Mekele (Quiha) with indication of the rainfall

seasons (belg and kirem) and the dry season (bega). The annual precipitation of 2006 was

755 mm, while the long-term average (1960-2006) of this station is 611 ± 148 mm (National

Meteorological Agency).

Cropping in our study area has as its most basic goal the increase in food security for households. The cropping emphasis is on cereals such as wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and the endemic fine-grained tef (*Eragrostis tef*), the latter being typical for the production of injera, the staple food of Ethiopia. If spring rainfall is sufficient, sorghum (*Sorghum bicolor*), maize (*Zea mays*) and finger millet (*Eleusine coracana*) are increasingly being grown (Slegers, 2008). Stews accompany the injera and, therefore, pulses like horse bean (*Vicia faba*), field pea (*Pisum sativum*), grass pea (*Lathyrus sativum*), fenugreek (*Trigonella foenum graecum*), lentil (*Lens culinaris*) and chickpea (*Cicer arietinum*) are cultivated. Pulses are grown as part of a crop rotation system due to their ability to fix nitrogen. Fallow land is uncommon (Nyssen *et al.*, 2008) as a result of agricultural intensification. A mixture of crops such as wheat-barley (*hanfets*) and field pea-horse bean is common to avoid total crop failure should there be drought or disease. Fruit trees, green vegetables and tuber crops are rare and mostly are produced on very small plots near to houses (Westphal, 1975; Nyssen *et al.*, 2008).

Soil properties such as depth, texture, fertility and water retention capacity largely determine crop productivity, and these are also considered by farmers when selecting cropping systems. Within a particular climate, soil characteristics vary with parent material and topographic position. Centuries of experience have provided local communities with an understanding of soil-crop relationships (Nyssen *et al.*, 2008) and an extensive nomenclature exists to denote

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soils of varying quality for cropping (Corbeels *et al.*, 2000; Nyssen *et al.*, 2008). In Northern Ethiopia, the best soils for agriculture are found on basalt, where even shallow soils on steep slopes are cultivated. Soils derived from limestone are less intensively cultivated and are often used as range or grazing land (Van de Wauw *et al.*, 2008).

Field survey

In order to investigate the cropping systems in the Northern Ethiopian Highlands, a field campaign was undertaken during July-September 2009. First, base maps were prepared for land units where farmers usually applied the same cropping system. Second, in each of the land units, interviews were held with local key respondents who had the best knowledge on cropping systems (Chambers, 1994). Key informants were farmers older than 40 who had been farming for many years. Semi-structured interviews in the field or in nearby villages included both specific and open-ended questions (Nyssen *et al.*, 2006) to allow the respondents to put forward issues that otherwise would not have been addressed (Wengraf, 2001). Consistency was checked by selecting several key informants per land unit and by consulting the local office of the Bureau of Agriculture. In total, 118 interviews were held, each of ca. 45 min.

Definition of the cropping systems

Cropping calendars were created for each land unit based on the period between the first day of sowing and the last day of harvesting. This corresponds to the maximum period for which crop cover may occur, taking into account that crops require a few weeks to germinate (Figure 3). Cropping calendars were produced for years perceived as dry, normal and wet by farmers. Therefore, in every area, farmers were asked to list dry, normal and wet years, and to define the cropping system they applied. Consequently, the annual precipitation maps

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prepared by Jacob (2010) could be used to define dry, normal and wet years in terms of the annual precipitation. Farmers' perceptions of the rainy season are, however, not only based on the total yearly precipitation but also on the distribution of rainfall throughout the cropping season. As indicated by Jacob (2010), there is a good relationship between total annual precipitation and the number of wet decades or the occurrence of early rains in February-May. Yearly precipitation thus largely reflects the characteristics of the rainy season and was therefore used as a proxy for the applied cropping systems.

Based upon the length of the growing season of the dominant crops, cropping systems were defined in accord with crop cycles as defined in previous studies (Funk *et al.*, 2003; Wubeneh & Sanders, 2006; Reynolds, 2008). In order to understand shifts in cropping systems in the different land units as related to rainfall variability, maps displaying the cropping system applied in each land unit were prepared for dry, normal and wet years in ArcGIS® 9.2.

Upscaling the cropping system patterns to the regional scale

The variability in cropping systems for the different land units and the relationship with rainfall was scaled up to the whole Northern Ethiopian Highlands using the 8 x 8 km² cells of the rainfall maps (1996-2009) (Jacob, 2010). Therefore, zones were delineated in the study area for which the same cropping system was applied in a dry, normal or wet year. As this zonation was different for upslope valleysides including structural flats compared to valley bottoms, these areas were considered separately. The zones were specified by defining Thiessen polygons between the studied land units. As a lower limit, the 2000 m a.s.l. contour line was used, as the study did not consider areas below that altitude. As an upper limit, the 3000 m a.s.l. contour line defined the transition to the high-altitude mountain zones, which were represented in the study area by the Seytan catchment.

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In order to convert the annual rainfall depth maps of Jacob (2010) to cropping system maps, dry, normal and wet years in each zone had to be defined in terms of annual precipitation. Therefore, histograms of the average annual precipitation (25 mm interval) for the 14-yr record of Jacob (2010) were analyzed per zone. Subsequently, maps were created showing the variability in cropping systems and duration of the crop cover over the period 1996-2009.

Results

Variability in cropping systems as related to rainfall

Based on when sufficient rain has fallen for sowing, farmers will design their cropping calendar so that for the selected crops, the length of the growing season reflects the expected rainfall. Such decisions are based on indigenous knowledge and take into account the very unreliable character of spring rains compared to the more reliable summer ones (Figure 2; Nyssen *et al.*, 2005). As the summer rains end rather abruptly in early September, the selection of crops is made at the beginning of the rainy season. For example, in the Lake Ashenge study area, early rains in April and May will motivate farmers to grow sorghum (*Sorghum bicolor*) in the valley bottoms as this crop has a long growing period (Figure 3). In contrast, if rainfall is only sufficient from July, the farmers will decide to grow barley (*Hordeum vulgare*) or wheat (*Triticum aestivum*).

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Figure 3. Cropping calendars in the valley bottoms of the Lake Ashenge study area in rainfall years perceived by farmers as dry, normal and wet. Major crops are indicated with a thicker line.

Based on all the studied land units, five types of cropping systems with distinct growing season lengths and typical plant associations were defined: short crop cycle (SC), short normal crop cycle (SNC), long normal crop cycle (LNC), long crop cycle (LC) and long two crop cycle (LTC) (Table 1).

Table 1 Properties of the cropping systems in Northern Ethiopian Highlands.

Cropping system	Duration of the cropping system (months)	Sowing month	Major crops
Short crop cycle	4	July/August	Barley (<i>Hordeum vulgare</i> , “white saesa” variety) and lentil (<i>Lens culinaris</i>)
Short normal crop cycle	5	June/July	Wheat (<i>Triticum aestivum</i> “selected” variety) with barley (“white saesa” variety) or lentil
Long normal crop cycle	6	May/June	Barley (“burguda” variety), wheat (“black” and “local” variety) and/or tef (<i>Eragrostis tef</i> “red” variety)

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Long crop cycle	9	March/April	Sorghum (<i>Sorghum bicolor</i>), Maize (<i>Zea mays</i>)
Long two crop cycle	10	January/February and July/August	Two crops in one year: barley (<i>Hordeum vulgare</i>)/ wheat (<i>Triticum aestivum</i>) and horse bean (<i>Vicia faba</i>)/ field pea (<i>Pisum sativum</i>)

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220 An analysis of spatial variability in cropping systems for 2009 when rainfall was generally
221 considered normal by farmers, indicated that three gradients occurred in the distribution of
222 cropping systems. First, a gradient occurred at the catchment scale as a result of topography,
223 soils and hydrology with longer crop cycles in the valley bottoms than on the valleysides and
224 structural flats. For example, near Korem, farmers applied a LTC system in the valley bottom
225 while a LC was applied on the valleysides (Figure 4). Second, a latitudinal gradient was
226 observed with a transition from shorter to longer cropping systems from north to south. This
227 gradient corresponds to the general north to south increase in precipitation. On the basis of
228 the cropping systems in the valley bottoms in 2009, a LTC system was applied near Korem,
229 and LC systems were applied in the Lake Ashenge area and LNC from Seytan to Ablo. Third,
230 an altitudinal gradient caused changes in temperature with altitude. This is of particular
231 importance to plant associations within cropping systems. For example, fenugreek as a
232 leguminous crop will not be included in crop rotations at high elevation but instead horse
233 bean will be cultivated. Similarly, among the barley cultivars, *burguda* will not be part of the
234 LNC at high elevations but instead *shewa* will be cultivated.

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Figure 4. Cropping system variability at the catchment scale (Korem, 2009). The photograph taken on 17 July shows farmers in the valley bottom harvesting the first crop and preparing the farmlands again for sowing the second crop. On the valleysides, mainly sorghum was cultivated that was only harvested in November and December.

As a result of the covariation between cropping systems and rainfall patterns, dry and wet anomalies in yearly precipitation will cause catchment-scale and latitudinal shifts in the cropping systems. At the catchment scale, switching from dry, normal to wet conditions will cause longer cropping systems to be applied, with the cropping system in the valley bottoms always retaining a longer cropping period compared to the valleysides. This is well illustrated for the Lake Ashenge study area (Figure 5). In the relatively dry year of 2004, a SNC was applied in the valley bottom while a SC occurred on the flanks. In 2009, when precipitation was perceived as normal by the local farmers, the valley bottom was under a LC, while on the valleysides a SNC was applied. Wet years, as in 2006, allow two harvests with the LTC system in the valley bottom and a LC on the valleysides.

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Figure 5. Cropping systems maps for the Lake Ashenge study area for years perceived as dry, normal and wet by farmers. A: dry year (e.g. 2004), B: normal year (e.g. 2009) and C: wet year (e.g. 2006).

Distribution of regional cropping systems (1996-2009)

The rainfall-related patterns at the catchment scale were also reflected in northeast-southwest shifts of cropping systems at the regional scale. Compared to the situation in normal years, cropping systems shifted southwards in dry years and northwards in wet ones (Figure 6A-D). Figure 6A-D shows the distribution of cropping systems for valley bottoms with increasing annual precipitation. The map of 2004 (Figure 6A), which was generally perceived by farmers as a dry year, shows that only SC or SNC were applied in the valley bottoms and SC on the valleysides, thus reducing the duration of the cropping season to four to six months. The maps of 2009 and 1999 show the situation in normal years, in contrast to below-average and above-average ones (Figure 6B and C). In general, LNC systems were applied in normal

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years with a cropping season of six months. In the below-average year of 2009 (Figure 6B), SC was in the north-northeastern driest part of the region while LC was found in the wetter southern part. Cropping season length in the valley bottoms varied from four to nine months. On the valleysides, SC was most apparent, reducing the cropping season length to four months. In an above-average normal year (Figure 6C), SC did not occur in the valley bottoms and LTC systems occurred in the southernmost part of the region. Cropping seasons then varied between six and ten months. For the valleysides SNC systems were widespread, which correspond to a cropping season length of five months. In an exceptionally wet year such as 2006 (Figure 6D), LC were most widely applied in the valley bottoms, with some LNC in the northeast and LTC in the south and at higher elevations. The cropping season therefore was generally nine months and varied between six and ten months. The LNC systems were most important on the valleysides.

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Figure 6. Cropping systems maps for valley bottoms in Northern Ethiopia as related to

rainfall variability. From left to right cropping system maps are shown with increasing total annual precipitation: A dry year (e.g. 2004), B below-average normal year (e.g. 2009), C above-average normal year (e.g. 1999), D wet year (e.g. 2006).

Discussion

The role of indigenous knowledge

Increases in sustainable agricultural output in poor dryland countries are the objective of many local, national and international research and development programmes, important also because of global warming and the effect on rainfall and its variability (Cooper *et al.*, 2008; Thomas, 2008). Successes have been achieved through improvements in landscape, water, soil and crop management, together with innovations from plant breeding programmes. However, the adaptation of new management schemes or innovations by local communities is often slow (e.g., Pulido & Bocco, 2003). This is often because new developments are not always applicable to traditional farming-social systems which can accommodate some uncertainty. In Northern Ethiopia, for example, the proverb ‘*After St. Michael’s Day feast (celebrated every 12th of the month) comes the rain, after the cock crows comes the dawn*’ (McCann, 1995, pg. 29) illustrates the importance of indigenous knowledge for farming communities, which will expect rainy seasons to start around mid-June and to end by early September.

Documenting indigenous knowledge and understanding the importance of local agricultural practices are important in order to increase agricultural output through encouraging the adoption of innovations by local communities (e.g., Hoque, 1984; Colfer *et al.*, 1997; Levasseur & Olivier, 2000; Araya *et al.*, 2011). Farmers’ traditional knowledge of soils is

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generally extensive. Local soil classification systems are available for many localities (e.g., Pulido & Bocco, 2003; Pimentel *et al.*, 2005; Nyssen *et al.*, 2008), and these are used to guide the selection of suitable crops. In dryland environments where rainfall is erratic and unreliable, farmers have also adopted flexible cropping strategies designed to cope with large variability in rainfall (e.g., Jodha, 1980; Stewart, 1985, Mugalavai *et al.*, 2008). Such information is important when assessing the agricultural implications of climatic variability (Smith, 2000; Stigter *et al.*, 2005; Cooper *et al.*, 2008; Thomas, 2008). However, reports on cropping strategies in relationship to rainfall variability remain rare.

Duration of crop cover and implications for land degradation

A succession of dry years in Northern Ethiopia, especially in the 1970s and 1980s, was associated with major land degradation by gullying (Virgo & Munro, 1978; Frankl *et al.*, 2011, 2012). For explanation, the length of the cropping cycles and thus the duration of the crop cover was never considered for accelerating erosion during dry years. However, with 33% of the land surface of Northern Ethiopian Highlands covered by crops, variability in duration of crop cover might be important for understanding the severity of previous land degradation cycles. As indicated in this study, farmers apply SC and SNC during dry years, thus limiting the cropping season to four or five months. This is in sharp contrast to the situation in a wet year, when LNC, LC and LTC are applied to increase the crop cover to sixteen months. This implies that, in wet years, cropland soils are better protected from water erosion (Styczen & Morgan, 1995; Gyssels *et al.*, 2005; Knapen *et al.*, 2007), and so are less vulnerable to the greater frequency of storms. In contrast, in dry years the period during which cropland soils benefit from protection against erosion by crop cover shortens during the early rainy season.

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Several studies stress the importance of crop cover characteristics throughout the rainy season in order to understand temporal variability in soil loss. For example, in Zimbabwe seasonal runoff and soil losses proved to peak not when rainfall was most severe, but rather in the early cropping season when the crop cover was highly variable (Elwell & Stocking, 1976). In the study area, Vanmaercke *et al.* (2010) shows that sediment concentration in rivers was highest at the beginning of the rainy season before crop cover was established. Similar concerns are also stated by Cyr *et al.* (1995) for southern Quebec (Canada), who stresses that crops which rapidly develop a good land cover should be cultivated in rugged terrain in order to protect the slopes against high-erosive rains in the early cropping season. In erosion studies, in Ethiopia and elsewhere, the importance of crop cover characteristics on land degradation is generally overlooked.

Conclusion

Farmers in the Northern Ethiopian Highlands have adopted flexible farming systems that take into account local environmental conditions as well as inter-annual variations in rainfall. Five cropping systems were identified with typical cropping season lengths: short crop cycle (four months), short normal crop cycle (five months), long normal crop cycle (six months), long crop cycle (nine months) and long two crop cycle (ten months). Each of these systems has a typical crop association. At the catchment scale, cropping systems on valleysides are of shorter duration than cropping systems in valley bottoms, which reflects contrasting soil and hydrological characteristics in these topographic situations. At a regional scale, a north-northeast to south-southwest change in cropping systems occurs, with crop calendar lengths increasing towards the south-southwest, parallel to variation in annual precipitation.

Farmers select a cropping system that matches the length of the rainy season, based on indigenous knowledge and dependent on the period during which the first rains of the rainy

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season are sufficient. Therefore, shifts in cropping systems occur at the catchment and at the regional scale with temporal variations in annual precipitation. As these shifts are the regional aggregate of farmers' decisions, which are shaped by indigenous knowledge, documenting indigenous knowledge and the impacts on agriculture is important, especially regarding climate variability. With 33% of the Northern Ethiopian Highlands covered by cropland, variability in the duration of the crop cover can also help with understanding previous land degradation cycles.

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