5. DISCUSSION

This chapter is organized sequentially, so as to parallel methods in Chapter 3 and results in Chapter 4, and integrates, wherever possible, findings from different sections. The first section presents the results from farmer surveys, indicating that there are significant differences in crop productivity among the heavily cultivated soil types. These are related not only to the climatic and physiographic properties of each soil type, but also to other factors relevant to specific fields, such as its age, size, and management. These factors, in turn, are influenced by historical and socioeconomic forces, which make it difficult to establish any direct, causal relationships to crop productivity without numerous stipulations.

The next section discusses results derived from the ASTER imagery, which provide a measure of the village's land shortage problem and farmers' residue management practices. There is also discussion of SLA-NDVI, its role in the soil loss equation, and, briefly, its potential application in future studies. The third section provides more thorough analysis of differences in soil spectra and quality indicators by comparing them to actual site descriptions. As average variability is greater among land use types than among soil types, the latter portion of this section discusses the high degree of variability that occurs within land use types (using individual samples) and indicates that certain practices may have strong influence on soil quality.

The last section provides convincing evidence to support the validity of soil loss estimates by synthesizing the discussions in previous sections to show that, on a qualitative level, there is a strong relationship between soil loss estimates, crop productivity, pre-harvest vegetative density, and soil nutrient content among the heavily cultivated soil types, as well as to ground truth observations of visible signs of erosion. This chapter provides the basis for the recommendations that appear in Chapter 6.

5.1 FARMER SURVEYS

The quality of survey data

There are several, fairly obvious limitations to the (2003) survey approach. For one, the units "bags" and "acres" are not precise units for measuring crop productivity (not all bags weigh exactly 100 kg and most farmers only reported integer values for their field's acreage); it has been assumed that differences in reported values for acreage and net yields (i.e., bags) become insignificant when aggregated for multiple fields to calculate average productivity. In terms of the survey itself (see appendix), many of its questions (i.e., those about management practices) only required simple "yes" or "no" responses. Thus, the survey could not account for salient details such as the amount of manure and the frequency of its application, the frequency/slope/ vegetation density of contour ridges, or how long the current method of tillage has been employed (e.g., every year since 1980). Moreover, farmers' responses to certain questions are certainly influenced by the fact that the survey is being administered by a rich, white male for research purposes. Data from socioeconomic questions such as "do you have a source of income other than agriculture?" are most susceptible to this type of influence. In spite of these limitations, results strongly resemble those of the 2002 survey and thus, even though both surveys had relatively small population sizes, the trends delineated in this section appear to be persistent, at least over the past two years.

Crop productivity

The averages for maize and wheat productivity reported in 2003 are consistent with values that have been reported by village farmers since the El Niño event in 1998. These values, 6.06 and 5.60 bags/acre, are well below average yields in most of East Africa's highlands for maize and wheat, which are 10 – 27 and 5 – 18 bags/acre, respectively (Nyoro et al., 2001).

Trends among the village's soil types (Table 4.1.1) indicate that fields in RU2 and RL1 have significantly lower productivity than fields in RU1, L1, and alluvial soil types. While it seems logical that alluvial fields would report the highest productivity, as these fields receive considerable nutrient inputs leached from the other highly cultivated soil types, the differences in productivity between the Northern region's RU1 and RU2 soils and between RL1 and L1 warrant closer inspection.

First, however, it is important to recognize that there are numerous factors at work here: field age (Table 4.1.2), management practices (Table 4.1.2), socioeconomic ownership (Table 4.1.9), and field size (Table 4.1.10) all have meaningful if not significant influence on crop productivity. Moreover, natural differences among regions/soil types such as climate, slope, and stoniness are equally important, as is the amount of natural vegetation (i.e., bush/graze) that remains in areas that are heavily cultivated (Tables 4.2.1 and 4.2.2). All of these interactions cannot be assessed, yet certain key trends do emerge.

The chief natural difference between RU1 and RU2 is slope; on the other hand, fields in RU1 and RU2 are comparable in that most were cleared before villigization, they have similar mean positive management practices ratings (22.9 and 20.1, respectively), they are dominantly owned by wealthier farmers (groups ‘A’ and ‘B’), and, as they coexist at the same altitude, they experience the same climate. Incidentally, average field size and the percentage of land used for cultivation (at the expense of natural vegetation) is greater in RU1 (7.3 acres and 86.4%, respectively) than in RU2 (5.1 acres and 79.1%, respectively). Thus, in the absence of any other notable differences, it would seem that RU2 fields should report higher or, at least, comparable productivity with respect to RU1 fields. Since productivity in RU2 is significantly lower than in RU1, RU2’s greater slope appears to be the primary reason for these fields’ lower productivity—greater slope contributes to greater rates of soil loss, which in turn contributes to reduced crop yields. This shall be further investigated in section 5.4, when soil loss estimates are integrated with crop productivity trends.

Between RL1 and L1, the primary, natural differences are that L1 receives a (slightly) hotter, drier climate and has stonier soils. These factors suggest that L1 would be predisposed to having lower productivity than RL1. Furthermore, RL1 has a much greater mean rating (18.2) and is less extensively cultivated (81.8%) than L1 (11.3 and 84.7%, respectively). Both are mostly owned by poorer farmers (groups ‘C’ and ‘D’). On the other hand, 44% of RL1 fields were cleared before or during villigization (the average year is 1976) and these fields have average maize productivity of 4.1 bags/acre compared to the 6.3 bags/acre reported by RL1 fields that were cleared after 1976; for L1, 80% of fields were cleared after 1976 (the average year is 1981) and these have average productivity of 7.5 bags/acre. At the same time, L1 fields are smaller (an average of 4.0 acres) than RL1 fields (an average of 5.3 acres). I am not convinced, however, that the typically younger age and smaller size of fields in L1 can be the sole explanation for why these fields are reporting significantly higher productivity than RL1 fields, especially since all other factors seem to favor RL1. I shall therefore return to this topic in section 5.3, as the potential role of soil quality indicators and their effects on productivity are discussed.

Management practices, field age and field size

As can be seen in Tables 4.1.2 and 4.1.3, the use of positive management practices is accompanied by significantly higher productivity for both wheat and maize (with the marginally significant exception of ox-plough tillage and maize productivity); correlations between younger field age/smaller field size and higher productivity are of equal significance.

Agriculture is often referred to as a diseconomy of scale, meaning that as field size increases, productivity tends to decrease. Although this phrase is usually reserved for plantation-sized fields versus smallholder farms, results in both 2002 (see appendix) and 2003 surveys (Table 4.1.10) show that the correlation is of high significance in Kambi ya Simba for productivity of fields larger than 5 acres versus fields smaller than 5 acres. There are several features distinct to larger fields that contribute to this outcome. For one, it is harder logistically for a farmer/family to monitor a large field and to pay attention to each individual or group of plants. Consequently, the qualitative amount of "care"—and often the quantitative amount of physical inputs (e.g., fertilizer, contour ridge frequency, light tamping of seedbed after rains)—that can be afforded to each plant is comprised. Moreover, larger fields demand more labor-efficient inputs, such as tractors and combine harvesters, and this necessitates to a greater degree practices like burning of residues. While these statements are applicable to "large" fields anywhere in the world, in Kambi ya Simba, "large" fields are also typically older. When these contributions are aggregated, it is unsurprising that field size exhibits the most significant correlation to both wheat and maize productivity of all the factors assessed in this study.

By field age, recently cleared fields exhibit a more significant, positive correlation to productivity for wheat than for maize. Since interregional and socioeconomic differences are minimal for this crop (again, wheat was and is still predominantly grown only in the Northern region and by wealthier farmers), the correlation seems quite acceptable *prima facie*—fields that have been cultivated for longer periods have suffered greater cumulative deterioration than younger fields, thus yields are lower. Although it is difficult to make an equally strong claim for maize that can be supported statistically (for it is heavily cultivated among all socioeconomic groups and regions), there is no compelling evidence to suggest that the negative relationship found between age and maize productivity would be spurious. Moreover, many of the oldest fields in the village were used solely for wheat cultivation until villigization, when, after redistribution, they became increasingly used for maize. For both crops, the correlation is bolstered by results in Table 4.1.9; between farmers of socioeconomic groups ‘A’ and ‘B’, fields are younger and crop productivity is higher for group ‘B’ than for group ‘A’ farmers, despite nearly identical mean management practice ratings. While farmers maintain that crop productivity levels were sustained up until villigization, it is quite likely that gradual declines did occur among older fields but these were offset by a relatively high rate of expansion into new lands. When expansion could no longer be sustained after villigization (as virtually all arable land had been cleared by 1976), and coupled with the resultant lack of natural vegetation around fields and increased use of tractors, productivity began to drop and, presumably, more markedly in the fields that had been cultivated the longest.

Drawing from section 2.5, the use of tractors is associated with higher rates of soil erosion caused both from quicker ploughpan formation and the fact that it is simply more difficult to till along natural contours by tractor. Thus, all other factors being equal, one should assume that fields tilled by ox-plough should report higher productivity than fields tilled by tractor. While a strong correlation between ox-plough tillage and higher wheat productivity supports this hypothesis ($p < 0.01$), results for maize do not; in fact, a weak correlation was found between tractor tillage and higher maize productivity ($p < 0.1$). Like field age, trends in wheat are easier to historically been grown chiefly by wealthier farmers, their relative affluence has afforded them with the option of using tractors for every growing season since villigization, exacerbating ploughpan formation and cumulative degradation. Accordingly, wheat productivity is lower for fields tilled by tractors.

In the case of maize, however, the finding that fields tilled by ox-plough have lower productivity than those tilled by tractors suggests that other factors/biases may be outweighing the influence of tillage on productivity. The strongest bias appears to be geographic, as 2002 survey results (in appendix), which had a more even geographic distribution, indicate that both maize and wheat productivity are higher for fields tilled by ox-plough than by tractor. Results are somewhat skewed in the 2003 survey because 13 out of the 17 maize fields in RL1 (76%) are tilled by ox-plough, whereas the proportions within other soil types are close to half-and-half. Therefore, RL1's fields tilled by ox-plough weigh heavily in the village average and, as discussed in the previous section, RL1 has significantly lower productivity than the other soil types. Removing RL1 fields from calculations, productivity for maize fields is 6.8 bags/acre for tillage by ox-plough and 5.7 bags/acre for tillage by tractor, which concurs with trends observed in wheat productivity by tillage practice, presumably for the same reasons.

Positive correlation between manure usage and crop productivity is more significant for maize than for wheat, as shown in Table 4.1.3. For wheat, this lower significance appears to be related to the fact that RU2 fields reported higher manure usage than RU1 fields—60% versus 45%, respectively—and, at the same time (from Table 3.1.2), RU2 contains 47% of the village's surveyed wheat fields versus RU1's

34%. As RU2 reported lower overall wheat productivity than RU1, the correlation to manure usage is less significant than might be the case with a more uniform geographic distribution of wheat fields. For maize, the correlation is highly significant among all soil types ($p < 0.005$). With both crops, these correlations are accepted *prima facie*: manure provides numerous positive benefits for soil fertility (as discussed in section 2.5) and, therefore, crop yield increases.

Negative correlations with residue grazing and crop productivity were significant for both maize and wheat, yet it is difficult to assess the extent to which the two are causally related. For one, trends in residue grazing are highly variable between years (e.g., only 26% of fields were reportedly grazed in 2002, compared to 42% in 2003), unlike other management practices, and questions about grazing intensity were not included in the survey (a farmer who only allowed livestock grazing once in the past year is, in practice, treated the same as farmers who frequently did so). For these reasons, it is difficult to assess the cumulative nature of this practice and, therefore, to attribute it directly to lower yields. Moreover, the decision to allow livestock to graze residues is largely controlled by socioeconomic forces—wealthier farmers with too many livestock may see no other option, whereas poorer farmers without any livestock aren't even presented with the option. The interactions between socioeconomics and this particular management practice (as well as the others) shall be discussed more thoroughly in the next section.

Of all management practices included in the survey, the presence of vegetated contour ridges had the greatest positive correlation to crop productivity (and was thus assigned the highest rating factor). This trend was highly significant for both wheat and maize fields; similar trends were found in the 2002 survey. Only 17% of the fields with vegetated contour ridges used stones for further support, and this had no significant effect on crop productivity. A larger sample size of fields with contour ridges supported by stones that is more evenly distributed among the village's soil types would be necessary to test for significant correlations, though it is interesting to note that half of this set of fields were owned by farmers of socioeconomic group 'D'.

There is compelling evidence to suggest that many farmers responded to the IMF/World Bank's Structural Adjusment Programs, which abolished subsidies for fertilizer and improved seed varieties in 1986, by constructing contour ridges. Out of the 31 fields with vegetated contour ridges owned by farmers who replied to this question, 71% built their ridges after 1986 and 41% of this subgroup constructed them from 1987 to 1991 (i.e., immediately after the subsidies were removed). By contrast, only 3 of the original set of 31 fields had contour ridges built before or during villigization. No correlation was found between contour ridge age and crop productivity for either wheat or maize.

In summary, there is strong indication that younger field age, smaller field size, and positive management practices (with the possible exception of preventing livestock from grazing crop residues) are significantly related to higher crop productivity for both wheat and maize. Since each of these management practices is designed to reduce soil erosion while simultaneously (in the case of manure, some contour ridges, and preventing residue grazing) improve soil nutrient content, such correlations are logical. Yet it is testimony to their importance that these trends emerged to such degree despite the multitude of interrelated and exogenous factors.

Farmers are in accord that all of the management practices included in the survey effectively combat productivity declines, yet, as mentioned in section 4.1, only 8 of the 80 fields surveyed utilize all of these practices. It is therefore necessary to discuss the socioeconomic factors that have inhibited their widespread implementation.

Socioeconomics

Although the socioeconomic data collected in this study is primarily related to agricultural holdings, most families in Kambi ya Simba appear to live below the $1 income/day poverty line. As is the case with all absolute, per capita poverty lines, such a statement is distorted by the presence of a large, informal economy and poorer farmers (groups 'C' and 'D') till by ox-plough. As the tractor is the more capital-intensive method of the two (farmers must rent the tractor and pay for fuel), it is logical that wealthier farmers report higher use, whereas poorer farmers often have no choice but to use the inexpensive, but labor-intensive, ox-plough. In addition, wealthier farmers usually have larger fields than poorer farmers (Table 4.1.10), creating further need for tractors. Some of the farmers of group 'D', however, do not own any cattle or livestock and may therefore be unable to till by ox-plough if oxen can't be borrowed. This forces these farmers to rent a tractor from another farmer, usually on credit, and may be partly responsible for why they report lower use of ox-ploughs than group 'C' farmers.

Manure usage is also strongly related to socioeconomic status, as wealth is largely measured by the size of one's livestock holdings, and, of course, the more livestock, the more manure there is for fields. Table 4.1.8 shows a clear decline in manure usage from socioeconomic groups 'A' to 'C'. This decline is partly related to a decline in the ratio of livestock head to field acres (calculated from Tables 4.1.5 and 4.1.6); for fields owned by group 'A' farmers, there exists an average 3.2 animals per acre, while for group 'B' farmers there is only an average 1.8 animals per acre. This discrepancy suggests that even if both groups of farmers rely heavily on the extensive grazing system (as they do), group 'B' farmers are not able to apply the same amount of manure per year to their fields as group 'A' farmers. At the same time, the large herd sizes amassed by both groups of farmers prevent all of their animals from being herded simultaneously; therefore, while some graze, others must remain penned at home, which allows for easy manure collection. This mechanism apparently contributes to the lower reported manure usage of group ‘C’ farmers in relation to group ‘B’ farmers, as ‘C’ farmers only have an average of 9.2 livestock per field compared to group ‘B’ who have 18.1 livestock per field, despite having a slightly greater livestock to acres ratio (2.0) than group ‘B’ farmers. For group ‘D’ farmers, their low livestock numbers (average 1.5 head per field) suggest that most keep their livestock penned, as each animal is of greater relative value than with other socioeconomic groups. For this reason, nearly all farmers in this group with livestock apply manure (i.e., more so than group ‘C’), yet due to their low livestock to acres ratio (0.4), very little manure is available for even distribution about their field(s).

The decision to prevent livestock from grazing crop residues is also largely a reflection of a farmer’s livestock holdings. The relationship appears to be inversely proportional, that is, group ‘A’ farmers, who have the most livestock, do the least to prevent residue grazing, whereas group ‘D’ farmers, who have the fewest livestock, reported the most adherence to this practice. While this correlation is logical *prima facie*—farmers with more cattle run out of forage quicker and thus turn to crop residues—it also shines light upon the relative value of soil quality to farmers in each socioeconomic group. Since poorer farmers have substantially fewer acres than wealthier farmers, each parcel of land is of greater importance to them and they are more dependent on maintaining its quality to meet subsistence needs. Wealthier farmers may justify the practice of residue grazing as a small soil quality sacrifice in exchange for high livestock-produce returns (i.e., better/more milk, wool, and meat). As poorer farmers do not have enough livestock to generate much supplementary income, they must strike a balance between crop and livestock management so as to best meet their needs for subsistence.

Despite the fact that constructing contour ridges requires capital investment and a short-term sacrifice in productivity, the use of vegetated contour ridges appears to be inversely proportional to wealth. This counterintuitive finding can easily be used to underscore the greater importance of soil quality to poorer farmers; however, it may also indicate the degree to which subsidy removal imparted an unequal distribution of panic among the village's farmers—poorer farmers were more affected and thus responded immediately by constructing contour ridges. This is supported by the finding that more than half of the fields with vegetated contour ridges owned by farmers in socioeconomic groups 'C' and 'D' had them constructed between 1987 – 1991 (i.e., 8 out of 14). By comparison, one quarter of group 'B's fields' contour ridges were constructed during this time (i.e., 4 out of 16) and none of group 'A' residue grazing—have the lowest individual practice ratings and thus in summation, these are outweighed chiefly by the higher manure usage (the second highest individual practice rating) reported by wealthier farmers. Even when ratings are no longer weighted, groups ‘A’ and ‘B’ fields, on average, employ more than two positive management practices while groups ‘C’ and ‘D’, on average, have fewer than two positive management practices per field. In all cases except group ‘D’, it appears that more positive management practices are present in wheat fields than in maize fields (Table 4.1.9), (group ‘D’ only has two farmers that cultivate wheat). As wheat is a cash crop, it appears more resources have been invested to ensure its productivity and to offset the cumulative degradation associated with fields of older age, which are mostly used for wheat.

In addition to traditional socioeconomic inequities (i.e., wealthier farmers have greater income, more land, and more livestock), there are also inequities among the village’s farmers in terms of regional land distribution (Tables 4.1.6 and 4.1.7). Wealthier farmers (52% of the survey population) own 84% of the land in the Northern region and, moreover, the wealthiest 16% (group ‘A’) own 40% of field acres in the Northern region. For this reason, the wealthier farmers own 86% of the village’s wheat acreage (group ‘A’ farmers own 36% of wheat acres), as virtually all wheat fields are located in the Northern region. Between soil types RU1 and RU2 and groups ‘A’ and ‘B’, the gentler slopes of RU1 are mostly owned by group ‘A’ (they have more than 5 times the amount of acres per farmer in this soil type). As result of being unable to cultivate the prime, RU1 soils of the Northern region, group ‘B’ farmers also keep relatively large estates in the Central and Southern regions, and even these are more sizeable than holdings for groups ‘C’ and ‘D’ (who have only minimal presence in the Northern region).

It does not necessarily follow from these discussions that wealthier farmers have higher productivity than poorer farmers, even though this may appear to be the case for maize crops in Table 4.1.9. As has been discussed, wealthier farmers do have substantially more property in the village’s most naturally fertile lands in the Northern region and also employ positive management practices to a greater extent than do poorer farmers. At the same time, wealthier farmers tend to have larger fields (Table 4.1.10), which have been shown to yield less per acre than smaller fields. Most likely a result of land redistribution during villigization, there is no strong relation between field age and socioeconomic ownership.

The only way to predict productivity from socioeconomic status is on a field-by-field scale, disaggregating certain features wherever possible. Thus one should not claim that, for two fields on soil type RL1, the field owned by a farmer of group ‘A’ should be more productive than the field owned by a farmer of group ‘D’ simply because group ‘A’ farmers typically employ more conservation measures. Such a statement neglects important details such as field age, slope, and size, all of which correlate to productivity trends to an equal if not greater degree than each constituent positive management practice. When these factors are held equal, however, it may be the case that wealthier have higher productivity than poorer farmers because of their greater utilization of soil conservation practices.

5.2 REMOTE SENSING

The quality of ASTER data

Overall, the quality of data provided by ASTER in both images and DEM met the basic needs of this project. ASTER images are “theoretically” correct to 50 m for geographic coordinates (i.e., UTM, latitude/longitude), ±10 m in elevation for DEM pixels, and ±5° for slopes over a horizontal distance of 100 m (Abrams and Hook, 2004; Orton, personal communication, 2003). While the October image was geographically correct to 15 – 100 m, the June image’s coordinates all differed from georeferenced coordinates by more than 100 m per pixel, which was accounted for as best as possible (section 3.2). DEM elevations were apparently accurate to ±10 m, based on georeferenced elevations, yet DEM-derived slope, as mentioned in section 4.4, had less resemblance to georeferenced slope. EOS radiometric corrections were not extensive enough to remove DN attenuation caused by varying topography, thus land use was mapped within each NSS soil type (to minimize variation in slope and altitude effects) and SLA-NDVI was developed (to improve cover estimates on a village scale).

Soil type and land use mapping

Since there are few compositional differences among the village’s soil types that are manifested strongly in the ASTER imagery (virtually all pixels possess some degree of ground cover), it is difficult to assess the accuracy of the soil type map and the methods employed in generating it (as it was done by hand rather than by assigning thresholds). It did, however, correctly classify 85% of the georeferenced points (or

94%, after finding that 9 of the georeferenced points appeared to be misclassified) and errors only occurred in intersections between soil types. It is quite likely that the mapped boundaries between alluvial/valley, RU1/RU2, and L2/valley soil types (the areas where misclassifications were most frequent), as well as the others, would differ to a small degree if soil types were to be traced on foot using a GPS. At the same time, accuracy in the soil type map would certainly have improved had the ASTER DEM slope image been more accurate, since many soil types are differentiated on the basis of slope, although the shaded relief image seems to have worked well as a substitute.

The land use map derived from the soil type map also appears to be mostly accurate in that it correctly classified 83% of the georeferenced points, and errors were mostly along intersections between soil types (which have unique land use thresholds) and between land use types of similar vegetation density (i.e., the threshold between 'dense bush/graze' and 'sparse bush/graze' is arbitrary, and georeferenced graze areas sometimes had less cover than 'fields with residues', which caused them to be misclassified remotely as 'fields'). It is important to recognize, however, that georeferenced points were not used in corroboration with the ASTER image to generate the land use map. It is impossible to classify all pixels' land use types accurately if one relies solely on remotely sensed data; there are always anomalies (e.g., grasslands with sparser cover than fallow fields) and the ubiquity of mixing within pixels. In crafting my methodology, I felt that the georeferenced site descriptions would serve greater use as validation for my land use map, rather than as a mold for its construction.

While it was necessary to map land use within each soil type due to the natural attenuation of DN values that occurs over change in elevation and topography, in the categories of ‘bush/graze’, it is difficult to assess the extent to which the lower DN values in the southern regions are related to the different, less leafy vegetation present here (see section 2.3) and not just natural attenuation. Based on observations made in the field, forested areas in the Northern region are much denser and taller than in the southern regions; cover estimates derived from SLA-NDVI were higher for ‘dense’ bush/graze in the Northern region than in the Central and, especially, the Southern region. On the other hand, surface cover estimates for fields were lower in the southern regions than in the Northern region despite ground observations in October-November 2002 that suggest the opposite may be true. While these observations do not undermine the quality of the report’s land use maps (as the threshold-defining process was performed within soil types to minimize such large scale, region differences), they do suggest that the cover estimates used in the soil loss equation may underestimate actual coverage in the Central and, especially, Southern regions. To better correct for this, it would have been necessary to take field measurements *in situ* with the October 2002 image, as qualitative observations such as mine are not sound bases for performing greater adjustments than that which was already performed via SLA-NDVI.

The extent of cultivation

The results in Tables 4.1.1 and 4.1.2 show that a staggering amount of natural vegetation has been cleared for cultivation and, moreover, there is virtually no room left for expansion. Even marginally suitable soil types such as RU3 and RL2 are extensively cultivated (i.e., more than 50%); about one quarter of the steep, stony valley soils are also used for cultivation. These are both recent phenomena (ca. 1990). While only a little over half of the village's alluvial soils are fields, there is the ever-present threat of flooding, which had previously discouraged farmers from growing crops in these areas (all surveyed farmers who had alluvial fields also had at least one other field located somewhere else, presumably to compensate in the event of flooding). In soil types RU1, RU2, RL1, and L1, less than 20% of bush/graze remains and, on average, only one fifth of this is 'dense bush/graze' (i.e., 4% of total land). In other words, there is very little natural vegetation remaining in these heavily cultivated lands to slow the speed of overland flow. The lack of natural vegetation is most considerable in the Northern region, as is the extent of cultivation in marginal lands. While this is consistent with the fact that most of the village's population lives in this region, it is also where slope is steepest and fields are oldest, thus it poses the greatest threat to crop productivity.

The areas of bush/graze remaining in the village are predominantly 'sparse', suggesting that (i)37.1(n)-20.0(i)37.1(n)a(,)10.1( )-70.2(p)-20.0(r)1

vllumia lilv hillv sils are the onl□ l rllsli bounded by exceedingly steep and stony valley walls, which are also effective in preventing grazing and cultivation. In all other areas, however, the higher presence of ‘sparse’ rather than ‘dense’ bush/graze is troubling. Since ‘sparse’ coverage, by definition, offers less protection than ‘dense’ coverage against erosion, and its use for grazing exacerbates this, there is likely to be increased encroachment in the near future as the quality of graze declines and livestock numbers increase. Moreover, the need for timber and fuel wood shall also increase in proportion to the village’s population, causing further encroachment on the village’s forest reserves, as well as the nationally protected Northern Highland Forest Reserve.

Residue management

Table 4.2.2 also shows the relative percentages of fields that appear to have residues present as opposed to those that have, presumably, been burned. Only fields in the Northern region (soils types RU1, RU2, and A) have a higher proportion of bare fields than fields with residues, which is largely a reflection of the fact that more than half of these fields are used for wheat. As mentioned in section 2.5, the practice of burning fields after harvest is still customary for wheat and thus it is quite likely that the proportions indicated in this table for the Northern region strongly correlate to the actual proportions of fields that are used for wheat as opposed to other crops. In the Central and Southern regions, approximately two-thirds of fields have residues present, which is similar to ground truth observations (where only bean fields appeared to be burned). All fields in marginal lands are predominantly covered by residues; from fieldwork in June/July 2003, a large fraction of fields in marginal lands appeared fallow during the peak of the growing season, so it is quite possible that many of these fields in the October 2002 image also have considerable grass and weeds present in addition to residues (i.e., they might have lain fallow for several growing seasons).

As discussed in section 4.2, fields that had residues present in the October image were predicted to have higher crop densities and lower MSI in the June image because they would afford fields with more protection against soil erosion, thereby facilitating less moisture stress, higher crop density and, presumably, higher crop yields (this assumes October 2002 residue management was, at a large scale, similar to October 2001). Since this correlation was only significant for the Northern region (Table 4.2.4) and, as previously mentioned, it is highly likely that most ‘bare’ fields in the Northern region are wheat, it seems that the correlation is less a product of the impact of residues in preventing erosion and more a product of other crops having greater NIR reflectance than wheat fields. As all wheat fields are monocultures and a wheat plant is typically shorter than a maize plant, this seems quite probable, especially since maize fields are often intercropped with beans and/or pigeon peas (giving them a denser understory layer). While this does not necessarily imply that wheat fields are less dense than other crops, maize fields do have greater leaf area index than wheat fields, which would cause a maize field to have greater NIR reflectance than a wheat field of equivalent density. Since the correlation was not significant in the Central and Southern regions (where fields are predominantly maize), more tests are necessary to support the notion that residue presence before the rainy season can effect an increase in crop density at maturity.

SLA-NDVI

SLA-NDVI was designed primarily to ameliorate radiometric differences that occur by altitude, but it is sensitive to any vegetation and soil type differences that may also occur by altitude (e.g., stoniness, pigmentation). It has potential applications for compensating for other topographically induced radiometric differences (e.g., slope and aspect), as well as moisture content (i.e., from MIR bands), and can be easily calibrated to predict canopy cover (section 3.4).

The fact that SLA-NDVI offers improved land use prediction over other commonly used vegetation indices is not particularly noteworthy; it is an inherent feature of its methodology. Land use predictions are always improved when a vegetation index is applied to subsets of a larger image (i.e., as was done in this report using the simple ratio), as it reduces the overall amount of variability to be explained by the vegetation index. Similarly, SLA-NDVI was derived by subsetting the village into altitudinal intervals (of 50 m), assessing soil line differences within these intervals, and then weighing these intervals accordingly so as to produce a regression equation for the entire village. Although this is not the same as band-wise regression (section 3.2), the inclusion of altitude makes the index more sensitive to regional differences in soil and vegetation reflectance. SLA-NDVI predictions would have been improved if the equation had been derived from more frequent altitudinal intervals (e.g., 10 m).

Nonetheless, to the best of my knowledge, SLA-NDVI is the first vegetation index to include altitude as a parameter. If SLA-NDVI were to be conducted on numerous ASTER datasets that have highly varied topographies, universal trends might emerge. In this scenario, a general version of SLA-NDVI could be devised, which would absolve the interpreter from performing the menial work of deriving the SLA-NDVI equation for his entire dataset, as the formula could simply be inputted into the band-math module included with image processing software.

As discussed thoroughly at the end of section 4.2, Table 4.2.5 shows that the seasonal SLA-NDVI differences for fields by soil type exhibit strong parallels to maize productivity by soil type (Table 4.1.1). In the next section, I shall discuss how similar trends by soil type are also present in quality indicators derived from DRS soil spectra and, in the last section, in qualitative soil loss estimates.

5.3 SOIL SPECTRA AND QUALITY PREDICTIONS

There are several important caveats that must precede the discussion in this section. For one, soil samples were taken during June, when crops were nearing maturity, and thus their predicted compositions are not necessarily representative of compositions that might be present after crop harvests. While this is cause for obvious limitations, on the other hand, conditions present at this time may provide a better indication of cumulative soil degradation. At this stage in vegetation growth, the uptake of plants has removed most available nutrients from topsoil, and deciduous species are in full bloom so there is little input from leaf litter. It would seem, therefore, that the most degraded soils would show the greatest deficiencies in nutrient contents at this general point in time. If samples had been taken earlier in the growing season or at the end of the dry season (when deciduous species are defoliating), there would be greater influence from inputs that have only short-term effects on soil quality (e.g., manure, leaf litter).

Second, the nutrient contents predicted for soils cannot be extrapolated to determine appropriate fertilizer amounts nor can they be compared to “ideal” levels, as the village’s nutrient cycles and crops’ needs have not been assessed in this study. To provide some basis for comparison, however, a study conducted in a similar village near Arusha (though of lower altitude than Kambi ya Simba), recommended levels of N > 0.4%, C_{org} > 3.5%, and exchangeable K > 0.8 me/100 g to sustain maize yields (Kaihura et al., 2001). As specific values cannot be recommended for Kambi ya Simba, values for quality indicators can only be treated qualitatively. One final consideration is that there is a high degree of variability that occurs for soil quality indicators within each land use type within each soil type. As this is the level at which soil quality indicators have been averaged for the soil loss equation, there is still substantial variability that has been lost in aggregation. Perhaps a better way to predict soil quality indicators at this level would be through isopleths, although a considerably larger sample size would have been necessary to do so.

The quality of soil spectra and DRS predictions

The spectral plots in Figure 4.3.1 indicate that variability is greatest in areas used for soil property determination. The absorptions around 1400, 1900, and 2200 nm, which are related to moisture content in clay minerals and the presence of OH^- radicals, show that despite air-drying, there may still be traces of water present in the samples. Yet overall variability (both in relative reflectance and first derivatives) is greatest in the 2400 – 2500 nm range, as well as in the VNIR, which is consistent with results published by Shepherd and Walsh (2000), Ben-Dor et al. (2002), and Selige et al. (2003). DRS calibrations also produced r^2 values in the range published in these and other similar works (see appendix). As only four of the ninety samples had predicted values that were outliers, this suggests that the calibration set of ten samples selected for laboratory analysis encompassed most of the spectral variability within the total population. Thus, assuming laboratory results are accurate, there is no indication that DRS predicted soil quality indicators should be inaccurate beyond their respective standard errors of calibration.

Spectral variation and composition among soil types

In Figure 4.3.2 it is important to observe that variability among soil types is greatest first in the VNIR range. This is primarily due to differing organic matter content and states of litter decomposition among arable soil types. As shown in Table 4.3.1, there is a linear decline in C_{org} values from north to south (i.e., by altitude), which is also documented in the NSS report. Since organic matter decomposition is partly controlled by climate, the cooler climate of the Northern region is less conducive to decomposition, whereas, as climate becomes warmer in the southern regions, decomposition occurs more swiftly. Though wetter climates, such as in the Northern region, typically experience faster decomposition rates, the relationship between soil moisture content and decomposition rate is not consistently direct—at concentrations beyond the optimum (depending upon the soil type), moisture content begins to impede decomposition. Yet in general, when there is ample moisture present in soils, temperature asserts a greater influence than moisture content in effecting decomposition rates (Paul, 2001).

While climate appears to be the dominant process controlling C_{org} content among the village's altitudinally defined soil types (since land use bias has been removed), erosion also seems to play a role. This is evidenced by C_{org} differences between RU1 and RU2: RU2's steeper slopes facilitate increased erosion, hence C_{org} values are lower than in RU1 despite the fact that the two experience the same climate and are generally similar in other regards (section 5.1). Similarly, RL1 has much lower C_{org} content than L1, suggesting that it too has experienced higher rates of erosion, especially because this region should receive a slightly cooler climate than L1 (owing to its higher elevation).

Variability is also important in the MIR range 2400 – 2500 nm where calibrations are made for clay content and K. While higher clay content and lower K are caused partly by greater erosion, differences in these properties may also be the result of compositional differences among soil types. I realize that up to this point I have minimized the role of compositional differences among soil types, however, DRS predicted clay content is much higher in L1 than for any of the other soil types (which all have clay content in the range 23 – 27%). It could be that L1 has naturally higher clay content than the other soil types (although this was not the case in the NSS report) or, perhaps, there is still some land use bias remaining in the average; other indicators (e.g., C_{org}, K, crop productivity) do not suggest that this is the result of increased erosion. Moreover, all other evidence (especially the lower average standard deviations in first derivative spectra) suggests that compositional differences among soil types are minimal and that land use has more a vital influence in affecting soil properties.

Spectral variation and composition among land use types

One of the key differences among land use types, as shown in Figure 4.3.3, is the slope of the “red edge” from 600 – 800 nm. The slope is lowest for bush and maize spectra and greatest for graze and maize spectra; similarly, C_{org} values (derived from this region of the spectrum) are greater for soils with graze than for bush, as well as for wheat than for maize (Table 4.3.3). This seems counterintuitive, since there should be a higher amount of leaf litter present in bush areas than in grazing areas, as well as a higher amount of residues in maize fields than in wheat fields—both of which should lead to higher C_{org} values.

The difference between bush and graze C_{org} values is related to fundamental differences between the two ecosystems. Tropical forests have some of the lowest soil organic matter content in the world, as these ecosystems support very high diversity of fungi and bacteria species, which cause rapid decomposition. Grazing areas, by contrast, have inherently lower biodiversity. Moreover, one of the most widely documented effects of overgrazing is that it quickly reduces diversity of graze species, as the most palatable and nutrient-rich species are the first consumed by livestock. There is also agreement that consistent, heavy grazing reduces plants’ ability to store adequate carbohydrates, causing a drop in vigor, failure to reproduce, and a slowdown of the carbon cycle (Strong, 2004). In summation, organic matter is less rapidly decomposed in areas used for grazing. Livestock feces deposited while grazing may also be partly responsible for higher organic matter content found in grazing areas.

In isolated areas of bush, however, such as the patches that occur within soil types other than valley/alluvial areas, sometimes the opposite is true. Their isolation from larger, forested ecosystems limits biodiversity; many of these patches contain only a few species of vegetation. In these instances, the high levels of leaf litter present are not rapidly decomposed and organic matter content is often much higher than in fields, grazing areas, or large areas of forest. This appears to be the case in fragmented areas of bush in soil type RU2, as shown in appendix and Figure 4.4.6.

The difference between organic matter content for wheat and maize appears to be more straightforward; maize fields from all regions are equally represented in the spectral average, whereas only fields from the Northern region can be included in the average for wheat. As discussed above, the Northern region's cooler climate supports higher levels of organic matter content. When differences between maize and wheat fields in just the Northern region are assessed, maize fields do indeed have higher organic matter content than wheat fields, most likely because of greater presence of residues.

As with soil types, the other region of the electromagnetic spectrum where variation is greatest among land use types is from 2400 – 2500 nm (related to potassium and clay content). It is here that clear trends begin to emerge for clay content among different land use types (for actual values, see appendix). On average, clay content is lowest for bush areas and highest for fields; grazing areas show strong variation (discussed in the next section) but are, overall, of intermediate clay content.

Since higher clay content is one indication of greater soil loss, this suggests that soil erosion is most pervasive in fields and least in areas of dense bush (as should be assumed).

The comparisons of quality indicators to 1989 values, as shown in Table 4.3.1, are useful mainly in that they indicate certain trends are still apparent among soil types, rather than that change or degradation has occurred within soil types. Thus, in this way they serve to validate the accuracy of DRS predictions, but with the important caveats that precede the table in section 4.3 (i.e., that the NSS samples were only taken from one site per soil type and the survey was conducted in February rather than June). For instance, between soil types RU1 and RU2, RU1 still has lower clay content and higher N and K (suggesting it experiences less erosion). Between RL1 and L1, L1 also has higher N and K, though as mentioned before, the clay content average for L1 seems anomalously high (and it is relatively low in the 1989 report) and there is no consistent trend between the two soil types for this quality indicator. For all soil types, trends and values for N are nearly identical between the two years and, as mentioned before, both results show a general decline in C_{org} by altitude. It appears that the alluvial soil type may have been flooded just prior to the 1989 survey, as clay content is very low (flooding deposits high quantities of coarser grained material) and N and K are exceedingly high (many nutrients are deposited as well). If so, then this may be why there is little correlation between 2003 and 1989 values for alluvial soils.

Spectral variation and composition within land use types

The plots of two soil samples from dense bush (Figure 4.3.4) show strong relative differences in NIR-MIR reflectance between 800 – 1300 nm, which is likely due to differing amounts of leaf litter present in the samples

There are strong superficial as well as compositional differences among the soil samples shown in Figure 4.3.5. From site descriptions, it appears grazing intensity is greatest in the area around sample **a** and lowest around sample **b**, with sample **c** being of intermediate intensity, though closer to **b** than **a**. Compositional differences support these observations mainly between samples **a** and **b**. Sample **a** has high C_{org} (4.9%) and it appears that nutrients N (0.12%) and K (0.70 me/100g) are severely depleted from overgrazing. Sample **b,** on the other hand, has relatively low C_{org} (2.9%, which is still higher than most areas of bush) and relatively high N (0.18%) and K (1.02 me/100g). C/N ratio for sample **b** (16.0) is substantially lower than for sample **a** (40.6), which suggests that the grazing intensity in and around sample **a** has caused serious declines in soil fertility. Sample **c** was taken from a valley side of slope ~20° and clay content is very high (34.4%), suggesting that the area has received severe soil erosion. K is relatively low too (0.84 me/100g), which is more likely a product of leaching from erosion than nutrient depletion from overgrazing. Intermediate values for C_{org} and N indicate that while erosion may be severe due to slope, the relatively low grazing intensity (as was observed) has not exacerbated the situation substantially.

In Figure 4.3.6, the maize fields have strong differences spectrally and compositionally, despite having relatively similar site descriptions. Based on its site description, Sample **c** would be predicted to have the greatest soil quality due to its high density of maize crops, tillage by ox-plough, and high presence of residues and grasses. This is supported by its soil quality indicators: of the three samples, **c** has the highest values for C_{org} (3.91%), N (0.24%), and K (1.18 me/100g). Between **a** and **b**, the chief superficial difference is that **a** is tilled by ox-plough, but maize is less dense, while **b** is tilled by tractor and crops are denser. These differences would suggest that sample **b** is of higher fertility simply because it has afforded greater crop density. This appears to be the case in terms of C_{org}, N, and K, which are higher for sample **b** (2.00%, 0.18%, and 1.22 me/100g, respectively) than for sample **a** (1.36%, 0.12%, and 0.77 me/100g, respectively), although C/N ratios are nearly equal. There is, however, a marked difference in clay content between these two samples: **a** = 19.3% and **b** = 30.3%. This does not appear to be the direct result of greater soil loss in the vicinity of sample **b**, as both fields are located on similar slope (< 2˚) and N and K content are higher for **b** than for **a**. These indicators do suggest that sample **a** has been recently cleared—the low values of clay and nutrient content strongly resemble those of samples taken from areas of bush/graze in RU2, and the sharp rise from 500 – 700 nm is very similar to sample **a** in Figure 4.3.5 (of grazing areas), suggesting that there were grasses present in the sample that had not fully decomposed.

The wheat fields shown in Figure 4.3.7 appear very similar spectrally and are mostly similar compositionally. Sample **a** appears the least healthy (from its site description) and has the lowest amount of N (0.15%) and K (0.57 me/100g) present among the plotted samples. Both **b** and **c** have very similar site descriptions, the only difference being that **c** is tilled by ox-plough, while **b** is tilled by tractor. Compositionally, these are very similar except that **c** has lower C/N ratio (11.4) and higher K (0.97 me/100g) than sample **b**, which has C/N of 12.8 and K of 0.64 me/100g. This could be due to less developed ploughpan in **c**, as it is tilled by ox-plough, and therefore it has experienced less nutrient leaching from erosion than sample **b** (which is also supported by much lower clay content for **c**). It is quite likely, however, that other factors such as field age and manure usage are responsible for these differences.

Soil quality of fields among soil types

As previously mentioned in section 4.3, Table 4.3.2 shows that trends in soil quality indicators parallel those of crop productivity for the soil types highly suitable for cultivation. With the exception of alluvial fields, which shall be handled subsequently, soil type RU1 reported the highest maize productivity and DRS predictions show that it also has the highest C_{org}, N, and K contents. L1 reported the second highest maize productivity, as well as the second highest values for the same quality indicators. RL1, on the other hand, has the lowest values all around. It is here that RL1's apparent advantages for crop productivity (discussed in section 5.1, i.e., more favorable climate, less stony, higher positive management practices rating, etc.) seem to be trumped by L1's higher nutrient contents and younger/smaller fields. While RL1's lower nutrient content is probably related, in part, to its older field age (i.e., there has been more cumulative degradation), it may also be related to shorter fallow periods or a lower presence of useful tree/shrub species (see Chapter 6 for a discussion of these) than in L1. The differences between RU1 and RU2, however, are still best explained by slope, as all soil quality indicators suggest that RU2 has experienced greater soil erosion and leaching than RU1 (i.e., higher clay content, lower C_{org}, N, and K).

It is not clear why alluvial fields, which report the highest productivity, tend to have intermediate values for soil quality indicators. However, alluvial areas typically show very high variability in soil quality because deposition patterns reflect the surrounding topography (i.e., deposition is greatest below areas of steep relief). It may be that samples were disproportionately taken from areas that receive relatively few alluvial deposits, and, therefore, these samples show little evidence of containing substantial amounts of leached nutrients from the lands above them. While there is high variability in quality indicators for this soil type (see appendix), only 7 fields were sampled, so data for alluvial fields are averaged from a smaller sample size than for other heavily cultivated soil types.

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fertility and have experienced greater erosion than L1. Since cultivation in this soil type is a very recent phenomenon (i.e., ca. 1995), and the area was (and still is) a grazing bastion, the high levels of C_{org} in comparison to L1 (and low levels of other nutrients) may be remnants of this former land use.

All quality indicators for the mbuga suggest that it is heavily eroded and of very poor fertility; in actuality, the mbuga is characterized in part by its expansive gullies and grazing has been forbidden to curb further degradation (unfortunately, this is rarely abided). Soil properties for the fields in the valley soil type are very similar to those found in areas of dense bush (i.e., low clay and nutrient content). Since cultivation in these soils is also a recent phenomenon, and fields are usually surrounded by large areas of bush/graze, it appears that the small-scale agriculture that occurs in these areas has, so far, had little impact on preexisting soil quality. Nonetheless, the low clay and organic matter content make these soils more susceptible to future erosion and the low levels of nutrients should inhibit crop productivity, unless supplemented by other inputs.

Soil quality of fields by management practices

Table 4.3.3 shows there are few emergent trends by field type, which appears to be mainly due to soil type bias among field types. For instance, virtually all ‘wheat’ samples came from the Northern region’s soils, while most ‘bean’ field samples came from the Southern region and most intercropped maize fields’ samples (i.e., maize/beans and maize/pigeon peas) were extracted from the Central region. Although bean and intercropped maize fields occur throughout the village (and thus their relative distribution in this report is, unfortunately, skewed disproportionately to their actual distributions in the village), wheat fields are predominantly located solely in the Northern region (and thus regional skewness is inherent). Yet due to the interplay of numerous factors (i.e., those discussed in section 5.1), which were not controlled for, no consistent trends were found for soil quality indicators among different field types in any region.

On the other hand, significant trends were observed within field types related to the use of certain conservation measures. As tillage method and the presence of contour ridges are the only management practices that overlap with farmer surveys and can be readily observed in the field when crops are present, it was not possible to correlate other important factors such as manure usage, residue grazing, and field age to DRS predicted soil properties.

Table 4.3.4 shows that there are no consistent trends for all field types related to tillage method. The use of ox-ploughs is significantly correlated to lower C/N ratios for *all* fields, but within field types, trends are not consistent and bean fields tilled by ox-ploughs actually have higher C/N ratios than those tilled by tractors. Only maize fields have higher contents of all nutrients when tilled by ox-ploughs. As farmer surveys indicated that, of all positive management practices, ox-plough tillage had the least significant effect on crop productivity, these results suggest that this may be because the practice also has little effect on soil quality and/or is consistently trumped by more important factors.

By contrast, vegetated contour ridges had the greatest positive effect on crop productivity in farmer surveys and there is evidence to suggest that the practice has had similar positive effects in terms of soil quality. Clay content is consistently lower for all field types—and significantly lower for *all* fields—when contour ridges are present, which indicates that they have likely been effective in reducing soil loss. The same is also true for C/N ratios, suggesting fertility may be higher, though this is not supported by the constituent C_{org} and N values, which are consistently lower for fields with contour ridges. Trends for both management practices are diluted by the fact that other factors related to soil quality (i.e., those attained from farmer surveys) could not be considered, and there has not been any attempt to account for the quality/frequency of contour ridges or the tillage methods employed in previous years.

Correlation of ground truth management practices to ASTER

While Table 4.3.6 shows that the management practices included in soil sample site descriptions are correlated to higher SLA-NDVI and lower MSI values for some field types, trends are only significant for *all* fields for the use of vegetated contour ridges in the pre-harvest (June) image. The fact that trends are not significant in the post-harvest (October) image is obvious—the use of these management practices does not imply that farmers will have greater quantities of residues on their fields, which is the only management practice that would cause them to have higher SLA-NDVI and lower MSI values in this image. And since only a single pixel corresponds to each soil sample site, the vegetation that may be present on contour ridges does not contribute to these values (no soil samples were extracted from the ridges themselves).

On the other hand, in the pre-harvest (June) image, the significant correlation between these indices and the use of vegetated contour ridges suggests that their presence contributes to greater crop density and less moisture stress, which manifests itself in greater crop productivity (shown by farmer survey results) and higher nutrient contents (shown from DRS predictions of quality indicators). As trends are not significant for tillage method, this finding is similar to results from farmer surveys (where tillage method had the least positive impact on crop productivity) and DRS predicted soil quality indicators (where tillage method had little impact on nutrient contents).

5.4 SOIL LOSS ESTIMATES

Wenner (1981) states that tolerable annual soil loss for deep, clayey soils in East Africa is in the range 12.5 – 17.5 metric tons/hectare for cultivated areas and 3.0 – 5.0 metric tons/hectare for grazing areas. Based on these estimates, most of the village's fields appear to experience soil loss above the tolerable range when slope factors are not included (Table 4.4.2). When slope factors are included (e.g., in Figure 4.4.7), some fields in RL1 and especially RU2 still experience unsustainable levels of soil loss. For all fields, when slope is greater than the threshold range for each ranking group shown in Table 5.4.1, estimated soil loss exceeds the tolerable range of 12.5 – 17.5 metric tons/hectare/year. As the tolerable range is much lower for graze/bush areas (as they do not receive constant topsoil replenishment from crop litter and agricultural inputs), Table 4.4.4 shows that estimated soil loss is well above the tolerable range for most of the village's grazing areas, especially valley and RU3 soils. Table 5.4.1 also contains slope thresholds for each ranking group that correspond to the tolerable soil loss range for graze/bush areas.

Table 5.4.1 Slope thresholds for each ranking group to maintain tolerable soil loss rates

Ranking	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Soil loss[1]	1.3	4.4	6.8	8.7	10	11.2	12.4	13.7	15.1	16.2	17.2	18.3	19.5	21.4	24.6
Fields[2]	22.3 - 26.9	11.2 - 13.6	8.6 - 10.6	7.4 - 9.1	6.8 - 8.4	6.3 – 7.8	5.9 - 7.3	5.5 - 6.9	5.2 – 6.5	4.9 – 6.2	4.7 - 5.9	4.5 - 5.7	4.2 - 5.4	3.9 - 5.1	3.5 - 4.6
Graze/bush[3]	9.9 - 13.4	4.5 - 6.4	3.2 - 4.8	2.5 - 3.9	2.2 - 3.5	2.0 – 3.2	1.8 - 2.8	1.6 - 2.6	1.5 – 2.4	1.3 – 2.3	1.3 - 2.1	1.2 - 2.0	1.1 - 1.9	0.9 - 1.7	0.7 - 1.5

[1] From Table 4.4.1; estimates are in 10^3 kg/ha/yr.
[2] Slope thresholds (in degrees) correspond to tolerable soil loss levels of 12.5 – 17.5 10^3 kg/ha/yr.
[3] Slope thresholds (in degrees) correspond to tolerable soil loss levels of 3.0 – 5.0 10^3 kg/ha/yr.

The spatial resolution of Figures 4.2.2 or 4.2.3 is great enough to allow farmers to identify the locations of their fields and, based on this location, to find its relative soil loss risk from Figure 4.4.1. With this risk estimate, farmers can approximate the slope of their field(s) and, using Table 5.4.1, calculate whether their field(s) experience tolerable rates of soil loss. Chapter 6 provides recommendations for farmers based on common trends within each soil type, as well as specific examples of measures that can be taken to reduce soil loss within fields of each soil type.

Differences in soil loss estimates among and within regions/soil types

Table 4.4.3 shows that there is a linear decline in cover estimates for fields with residues from north to south. As discussed in section 5.2, it was observed during October 2002 fieldwork that fields in the southern regions actually had greater quantities of residues present than those in the Northern region; thus, for the southern regions, cover estimates are likely lower than actual cover and, consequently, soil loss estimates are higher than might otherwise be the case. Nonetheless, even if soil loss estimates have reduced interregional accuracy, they can still be used to prioritize the areas of relatively highest soil loss risk within regions. The same applies to grazing areas, which exhibit a similar decline in cover estimates from north to south, although this trend was supported to some degree by ground truth observations. Again, this problem is not inherent in the methodology used to derive soil loss estimates and the attenuation could only be fully ameliorated by better radiometric correction of DN attenuation (performed by EOS) or using *in situ* field measurements.

The attenuation also manifests itself in Figure 4.4.7: the curves for soil types RL1 and L1 occupy a much smaller range on the overall spectrum than do the curves for the other soil types, as soil loss estimates are partly based on SLA-NDVI values (which are affected by the attenuation of DNs, as described in section 5.2). Nonetheless, there are several important trends that can be seen by looking at estimated soil loss distributions within each soil type. Since K-factor parameters are fixed within each soil type, plots are only responding to changes in altitude (i.e., rainfall energy) and surface cover. RU1 and RU2 plot similarly, with nearly standard distribution from ranks 3-4 to 12 and peaking towards the high end of the spectrum. As the curves' apices are in the high range of the spectrum, this suggests that the fields at greatest risk for soil loss have both low residue coverage (i.e., wheat fields) and are concentrated at the highest altitudes where rainfall energy is greatest (i.e., near the Northern Highland Forest Reserve). This is supported by ground truth observations, as the greatest concentrations of wheat fields are found at the highest altitudes (tapering off at lower altitudes and, ultimately, in the southern regions).

Between RL1 and L1, both curves exhibit peaks in the high range of the spectrum, with RL1 peaking around rank 14 and showing skewness to the left and L1 peaking around rank 11 and displaying near-Gaussian distribution. The differences between these two distributions is mostly due to the contributions of surface cover percentages, rather than altitude, as there is little altitudinal variation within each of these soil types (unlike RU1 and RU2 in the Northern region). In L1, the Gaussian distribution suggests that there may be one crop, e.g., maize, that is dominantly grown and its residues offer intermediate protection, whereas the portion of lower risk may correspond to fields that are intercropped (e.g., with pigeon peas), offering greater residues, and the portion of higher risk to be fields that are burned (i.e., bean or maize monocultures). For RL1, the left-skewed distribution indicates that there is little continuum, and the presence of two peaks in the curve (the other, less discernable, occurs between 8 and 9) suggests that there may be two distinct crop types/management practices being employed in this soil type. Based on ground truth observations, approximately one in three maize fields is intercropped (e.g., with pigeon peas, sunflowers, or beans), which may correspond to the first, smaller peak, while the remainder are monocultures or intercropped solely with beans, which, when combined with fields that have been burnt, may correspond to the second peak.

The histogram of soil loss rankings for fields in the alluvial soil type does not conform to those of the other soil types: it exhibits a concave shape, whereas the others are mostly convex. As this soil type is not confined to a particular region, the R-factor (rainfall erosivity, i.e., elevation) asserts a sizeable influence on soil loss estimates in addition to surface cover. Most fields are concentrated in the “low” soil loss range (especially rank 1), due to high surface cover (Table 4.4.3, see section 5.2 for reasons for higher cover), and are likely maize fields. The even distribution in the middle section of the curve (i.e., from ranks 4 to 14) represents fields of intermediate surface cover with variation in soil loss induced largely by altitudinal differences. The high frequency of rank 15 fields, which is a greater proportion than for any other soil type, corresponds to burnt fields at high altitudes (i.e., greater than 1750 m). Since the high fertility of alluvial soils can sustain longer periods of crop growth, crops in these fields may have matured later than in other fields and would therefore have been burned more recently, causing the spike at rank 15.

Validating soil loss estimates

As shown in section 4.4, several tests have been performed to determine whether the soil loss estimates generated in this report may be a useful predictor of crop productivity among soil types, vegetation health in the pre-harvest (June) image, and soil nutrient contents (i.e., N and K). In general, results in Figures 4.4.8 and 4.4.9 suggest that, indeed, soil loss estimates appear to serve these functions.

The difference between Figures 4.4.8 and 4.4.9 is important: in Figure 4.4.8, correlations between June vegetation density (i.e., SLA-NDVI) and soil loss estimates are consistently lower than implicit correlations between June and October vegetation density; in Figure 4.4.9, which shows correlations only for fields in the heavily cultivated soil types, the opposite appears to hold. The relative strengths of correlation coefficients in Figure 4.4.8 respond directly to the amount of natural vegetation (especially dense, coniferous vegetation) present in each of the plotted soil types. This should be expected, as natural vegetation exhibits less change in density over the course of a year than do fields (which was the basis for the method of mapping land use that was initially experimented with, as described in section 3.2) and, therefore, correlates more strongly. Yet, for areas of bush/graze, this natural correlation is diluted in soil loss estimates when factors of soil quality and elevation are included. USLE estimates are not intended for application in areas of dense bush/graze (and have less proven success in areas of sparse bush/graze as well); for instance, while higher organic matter content is useful in fields for preventing soil loss and increasing crop yields, lower organic matter content is an indication of a thriving tropical forest. Thus the validity of soil loss estimates in terms of predicting pre-harvest vegetative density is only bolstered by the results for fields, shown in Figure 4.4.9.

While the correlation coefficients in Figure 4.4.9 are uniformly low (all are below 0.2), due to the large sample size for each soil type (> 20,000 pixels), all correlations between soil loss estimates and pre-harvest vegetative density are highly significant ($p < 0.0001$). More importantly, they are consistently stronger correlations than the inherent correlation between SLA-NDVI values for the two images. Most of the correlation strength, however, is inherent (as shown by the close proximity of plotted points, especially in soil types A, RL1, and L1), which suggests, as should be the case, that greater surface cover on fields before the rains is linked to greater health/density when crops mature. However, the remaining portion of the correlation comes from the additional factors included in the soil loss equation—soil properties (in the K-factor) and rainfall energy (in the R-factor). This is especially true for the diverse assemblage of crop types in soil types RU1 and RU2, as there is less of an inherent correlation between SLA-NDVI values and greater change with respect to elevation. If slope factors could have been used to predict soil loss risk for each pixel, correlations to pre-harvest density might have been further improved.

There are other correlations of equal importance that, on a qualitative level, strengthen the validity of soil loss estimates, as shown in Figure 4.4.10. Trends are fairly consistent for maize productivity, SLA-NDVI difference (e.g., change in fields' vegetation health/density between the two images), and nutrient content (N and K) with respect to soil loss estimates that subsequently include the slope factor. In other words, this indicates, as should be expected, that fields that experience greater soil loss suffer in terms of crop productivity, crop growth (i.e., change in density), and nutrient content. As discussed in section 4.4, with the exception of the alluvial soil type, RU1 has the lowest estimated soil loss, the highest maize productivity, the greatest SLA-NDVI difference, and the highest contents of N and K. L1 is consistently second, while RU2 and RL1 alternate as having the lowest standardized values for these parameters.

The differences in crop productivity among soil types have already been discussed in section 5.1, as have the differences in seasonal SLA-NDVI values (sections 4.2 and 5.2) and nutrient content (section 5.3). The explanation for why the alluvial soil type may not conform to trends for seasonal SLA-NDVI difference and nutrient contents has also been discussed already, in sections 4.2 and 5.3, respectively.

Between soil types RU2 and RL1, there are several factors that may explain their alternating standardized values in Figure 4.4.9. For one, median soil loss estimates for RU2 fields *without* slope factors, as shown in Figure 4.4.7, are lower for RU2 than for RL1, and RU2's are also lower than RU1's. Thus, all other factors being equal, in areas of low slope, RU2 fields should exhibit trends in productivity, nutrient content, etc., similar to RU1. However, since RU2 contains a greater range of slope values than both RU1 and RL1 (as well as A and L1), if RU2 fields' slope values are unequally distributed within the farmer survey and soil sample populations, then alternating values across these parameters should be expected unless distribution is skewed entirely in one direction (e.g., all are below 5˚, like the other soil types' fields, or all are above 5˚). As RU2 has consistently higher maize productivity and nutrient content than RL1, it appears that RU2's population is skewed disproportionately with respect to slope in that most fields have slope less than 5˚ (if most fields had slope greater than 5˚, then one would expect productivity and nutrient content to be lower than RL1, as, theoretically, values for these parameters would suffer from increased soil loss). Although slope values are unknown for the population of fields represented in the survey data, values in the soil sample population are known, and most are below 5˚, which suggests that a slope bias may be present (the actual distribution of slopes within this soil type on the ground are, of course, unknown, so it isn't possible to judge how strong this bias may be). Yet SLA-NDVI difference, which is not affected by skewed distributions, as all fields' pixels are represented, conforms to the estimated soil loss trend between RU2 and RL1, as well as for the other soil types (i.e., RU2 experiences greater soil loss and thus has a lower SLA-NDVI difference). In theory, if a larger population of RU2 fields were surveyed and sampled, then trends for productivity and nutrient content should more closely resemble trends for soil loss and SLA-NDVI estimates, with RU2 exhibiting consistently lower standardized values than all other soil types.

Correlations to ground truth observations

To supplement statistical correlations, Figure 5.4.1 shows a version of the soil loss map with numbers (1-16) that correspond to a set of photographs of ground truth observations (Figures 5.4.2 to 5.4.17). These photographs were taken during both periods of fieldwork (October-November 2002 and June-July 2003). Only the 2003 photographs were georeferenced, thus numbers on Figure 5.4.1 correspond to the exact locations shown in photographs; all of the locations in the 2002 photographs were returned to and georeferenced in 2003, with the exceptions of Figures 5.4.14 to 5.4.16, where the best possible attempt has been made to accurately situate them. These photographs show that soil loss estimates succeeded in identifying several areas where gullies and severe erosion are apparent. In addition, they provide the reader with an indication of the range of land uses that accompany the spectrum of soil loss estimates.