Uncertainties, sensitivities and robustness of simulated water erosion in an EPIC based global-gridded crop model
By T. W. Carr et al.

Reply to Anonymous Referee #3

Dear reviewer, we appreciate your thoughtful comments and have responded to each in the following (Referee comments are printed in purple and are each addressed below).

This manuscript describes a study to characterize global soil erosion rates on cropland using the exploration of a large parameter space of driver data and erosion models. Starting with global information on climate, soils, agricultural practices, and field properties, the authors calculate representative erosion rates. In a series of experiments, they show the sensitivity of the model to driving inputs and parameter assumptions. They evaluate the model results against a large dataset of observed soil erosion data. The authors conclude that the model results are very sensitive to assumptions about management strategy, and the accuracy of the model is limited by a lack of field observations for calibration and evaluation.

In general this manuscript is well written and simple enough to understand. However some key information is lacking in the main text of the manuscript, and some of the results seem rather suspicious, possibly because of artifacts in the input data. In particular, the headline numbers for global soil erosion, and the mapped model output, appear to be strongly influenced by erosion in mountainous areas, where in reality land use for agriculture may be much more limited than the model assumes. These issues need to be addressed in a revision before the manuscript is ready for publication.

Our experience (not only from modelling, but also from field work, excursions and own observations and measurements) shows that in some mountainous areas the erosion rates reaches very high levels. But to some extent you are right and we considered your objection. Below, when answering other comments on this issue we will try to demonstrate in detail the situation in mountains. We will provide also some photos.

Looking at the model results in Figure 2a, what stands out immediately is that very high rates of erosion are plotted in many regions of the world where I would not be sure that there is any significant amount of agriculture, including the central highlands of Borneo, the Himalaya, eastern Madagascar, South Korea, and parts of the Alps. These are indeed high-rainfall/high slope regions and in some of the area agriculture is practiced. But where there is cropland, it almost certainly must be limited to valley bottoms or other low-slope areas, or only performed with substantial investment in erosion mitigation measures, such as terracing.

Digging deep into the manuscript supplementary materials, I discovered that the actual crop distribution data used in this study (5’) comes from Portmann et al. (2010). This citation, and explanation for how the crop areas were determined, must be moved to the main body of the text. It appears that Portmann et al. (2010) do not use slope or any other topographic characteristics in determining the spatial allocation of cropland in their crop area maps. Furthermore, 5’ resolution is probably too coarse even in the authors’ own admission to accurately determine appropriate mean slope classes for their soil erosion calculations.

The reference to Portmann et al. (2010) is listed in Table 3 in the main text, which summarises the field management assumption and aggregation of model outputs.

We extend the reference to table 3 on line 191. "*Table 3 summarises the field management assumptions of the baseline scenario used to aggregate erosion rates in each simulation unit and region.*"

We agree, that in some mountainous areas the erosion rates obtained by modelling do not represent typical rates. However, it is not the case for all mountains. The values are overestimated most probably in mountains of temperate areas such as Europe (Alps), Korea and Japan and also in some tropical rice grooving regions on tropical Monsoon Asia (such as Borneo). However, in many mountainous areas in tropics the land is cultivated, and maize and wheat are grown even in very steep slopes and often without any soil conservation practices or conservation practices are used with insufficient efficiency. We attached a collection of photos demonstrating these phenomena. In the tropics, agriculture is very active in mountains especially for four reasons:

1. While in temperate areas such as Europe the temperature is limiting factor of agriculture and in higher altitudes (several hundred meters above the see level) it is too cold for most crops and if agriculture exist there, it is mainly grazing. In contrary, in tropics the temperature is sufficient also in high mountains.

2. The limiting factor in tropics is drought. Therefore, mountains having more rainfall and less heat are popular agricultural area. Very good example is Uganda, where the whole flat central part of the country is too dry and it is used only for grazing, while steep mountains in west and east peripheries of the country are intensively cultivated. The same is in Madagascar and in whole Latin America where mountains are more agriculturally exploited than lowlands.

3. In tropics the weathering crusts are very thick and so the loose materials constitute thick soils. Tropical soils are poor in organic matter so the difference between topsoil and subsoil is not very big. These soils can be exposed to extreme erosion rates much longer than thin soils of temperate areas, so farmers do not feel the decrease of fertility and production potential. It is decreasing slowly, and they do not realize the impact of erosion.

4. In developing countries, a great portion of land is still under hand management of small family subsistence farming. These farmers can cultivate steep slopes easier than farmers who use heavy machines.

Some examples from our own field work, where the extreme exploitation of steep slopes exists are following:

1. In Latin America, especially in mountains with volcanic rocks are cultivate even in extreme slopes and here maize is dominant crop (see photos from El Salvador).
2. Mountainous area of Sub-Saharan Africa: Extremely steep slopes are cultivated, many crops with low conserving efficiency are grown (such as cassava and other sweet potatoes, beans, maize, etc.), there are terraces, but these are not really horizontal but inclined so they reduce erosion partially but not much (see photos from Uganda and Madagascar)
3. South and East Asia: In this region the major crop is rice which is usually grown on paddy field with flood irrigation. Therefore, the large mountainous areas are well terraced and well protected from erosion. However, there are also very large mountainous areas which are not terraced at all and steep slopes are cultivated. They are growing various crops there such as

dryland rice, tea, fruit trees, sugar cane, etc. For example, in large part of southern China the rice terraces are only in valley bottoms occupying minor areas and all steep slopes occupying majority areas are used to grow sugar cane without any soil conservation.

An explanation and further discussion of the resolution of slope input and cropland distribution data follows below

These limitations mean that the headline numbers for erosion (e.g., lines 25-26 of the abstract), and much of the results are likely to be skewed by calculations that are not realistic, because they are biased by high-slope/high-precipitation areas where in reality, agriculture is not practiced at all, or only in very limited and specialized forms, e.g., agroforestry, and perennial crops such as tea and orchards. This source of uncertainty needs to be addressed more thoroughly and the methods presented more transparently before this manuscript is suitable for publication.

Finally, it would be interesting if the authors performed a "reality check" on their erosion numbers. With some of the extreme values that they calculated, could agriculture be sustainable at all? How long would it take before most soil is completely eroded away?

Unfortunately, in many mountainous areas especially in tropics conventional agriculture with very bad management is practiced and it has huge negative impact on land. We demonstrated it by photos. In many mountainous areas agriculture is not sustainable at all. But unfortunately, despite of that in many areas the destructive land management is going on and poor farmers are destroying the land completely. We even do not know how many cases like this occur. We have examples also from Slovakia, mainly historical but also recent. There are known cases that some slopes were cultivated just 10-20 years and then one extreme storm event removed all soil and the field was abandoned. In tropics frequently happens that when the field is destroyed, it is abandoned for 5-10 years being fallow and then cultivated again, but there are many cases also when slope is cultivated for 5-7 years and destroyed once for ever. See attached photos.

There are indications of this problems also in literature, for example Montgomery (2007) calculated mean erosion rate under conventional agriculture (n= 448) to be over 3.9 mm (what is ca 60 tons per hectare). Of course, such agriculture is not sustainable at all. He concluded: "A direct implication of the imbalance between agricultural soil loss and erosion under both native vegetation and geologic time is that, given time, continued soil loss will become a critical problem for global agricultural production under conventional upland farming practices." Catastrophic effects of agriculture on land discuss Pimentel and Burges (2013). They argue that annually 10 million ha of cropland is abandoned due to deteriorating production potential caused by erosion. Further, they estimate that recently the world cropland covers 1.5 billion ha but since the beginning agriculture people abandoned 2 billion ha of crop land. So, more soil is already destroyed and abandoned then what is still used.

Lines 122-123

What is the justification for choosing the "most common slope"? At the very least, wouldn't it make more sense to choose the lowest slope class in each 5' gridcell? At least until all of the area in the slope class is filled by agricultural land use before moving to the next steeper class? If not, the authors' choice of modal slope class should be justified with citations.

The most common slope is determined by the slope class covering the largest area in each simulation grid. Slope classes are taken from a global terrain slope database (IIASA/FAO, 2012) and are based on a high-resolution 90 m SRTM digital elevation model. We assume that the slope class representing the largest area in each simulation unit is most likely covered by the largest area of cropland. This builds on the idea that a spatially extensive and diverse landscape can be represented by a single "representative field" characterized by the prevailing combination of topography and soil condition found in the landscape. This method is designed to represent differences in large-scale global crop production with an emphasis on the most important global crop production regions.

We clarify the concept of the representative field on line 120: "*Each simulation unit is represented by a single field characterized by the prevailing combination of topography and soil conditions found in the landscape. Each representative field has a defined slope length (20 – 200 m) and field size (1 – 10 ha) based on a set of rules for different slope classes (Table S1). The slope of each representative field is determined by the slope class covering the largest area in each simulation unit (Table S1). Slope classes are taken from a global terrain slope database (IIASA/FAO, 2012) and are based on a high-resolution 90 m SRTM digital elevation model.*"

Slope input data is an important uncertainty for simulating global water erosion estimates as we cannot identify cultivated slopes on a global scale. This will be discussed in the revised paper by addressing: (i) the simulation of extreme values on steep slopes including the proposed 'reality check'; (ii) the intention behind using the most common slope; and, (iii) an ideal scenario, where cultivation is limited to the flattest terrain available. We used Italy as a test case for a comparison between water erosion rates simulated under the proposed ideal slope scenario and the slope scenario based on the most common slope. We chose Italy because it has large maize and wheat cultivation areas, which are located on both flat terrain in the north and in hilly regions in the south, and thus the country represents a diverse landscape with a wide range of possible water erosion rates. We add a comprehensive discussion addressing each slope related issues after line 380:

"…High water erosion rates on steep slopes exceeding 100 t ha^{-1} are also included in the field dataset compiled for this study. However, regional erosion assessments in mountainous cropland conclude that areas with extreme water erosion rates are mainly limited to marginal steep land cultivated by smallholders (Haile and Fetene, 2012; Long et al., 2006; Nyssen et al., 2019). Moreover, efforts to remove marginal farmlands from agricultural production and programs to improve land management on steep slopes have reduced high water erosion rates in several mountainous regions (Deng et al., 2012; Nyssen et al., 2015). Nevertheless, in many regions upland farming still produces extremely high erosion rates and recent pressure through increasing population and crop production demands has resulted in re-cultivation of hillslopes and a reduction of fallow periods, which limits the recovery of eroded soil (Turkelboom et al., 2008; Valentin et al., 2008). In an ideal scenario where farmers cultivate the flattest land first before moving to the next higher slope, unsustainable water erosion rates in mountainous regions would be substantially reduced. However, next to topography, the distribution of cropland is determined by climatic factors and various socio-economic factors such as competing land use and land tenure (Hazell and Wood, 2008; Nyssen et al., 2019).

To analyse the sustainability of simulated maize and wheat cultivation systems exposed to high erosion rates, we compared simulated annual eroded soil depth with a global dataset on modelled sedimentary deposit thickness (Pelletier et al., 2016). The comparison shows that at 4 % of grid cells permanent maize and wheat cultivation would not be sustainable as the whole soil profile would be eroded at the end of the simulation period (Fig. S11). Most of the unsustainable agriculture is simulated on steep slopes. Although we account for conservation techniques and cover crops, we do not imitate the highly complex farming practices involving intercropping techniques and fallow periods, which are common *on hillslopes typically manged by smallholders (Turkelboom et al., 2008). Moreover, we assume that the slope class representing the largest area in each simulation unit is most likely covered by the largest cultivated area. This builds on the idea that a spatially extensive and diverse landscape can be represented by a single "representative field" characterized by the prevailing combination of topography and soil condition found in the landscape. This method is designed to analyse the differences in large-scale global crop production systems with an emphasis on the most important crop production regions. However, this setup might not capture the complex distribution patterns of cropland in mountainous terrain.*

The uncertainty in cropland distribution can partly be reduced by developing a higher resolution global gridded data infrastructure, which is currently not available for EPIC-IIASA. However, due to the large uncertainty in global land cover maps (Fritz et al., 2015; Lesiv et al., 2019), an explicit spatial link between cropland distribution and the corresponding slope category cannot be established without on-site observations. We test the impact of this uncertainty for erosion estimates in Italy, where large maize and wheat cultivation areas are distributed on both flat terrain in the north and mountainous regions in the south. In an ideal scenario where cropland is limited to flattest land available per grid cell, median simulated water erosion in Italy would be reduced to tolerable levels below 1 t ha^{-1}. However, in a scenario, where the most common slopes per grid cell are cultivated, median simulated water erosion increases to 14 t ha^{-1} due to high water erosion simulated in Italy's mountainous regions (Fig. S12). This suggests a high uncertainty in global water erosion estimates due to uncertain spatial links between maize and wheat cultivation areas and different slope categories."

The following two figures addressed in the discussion will be added to the supplementary information.

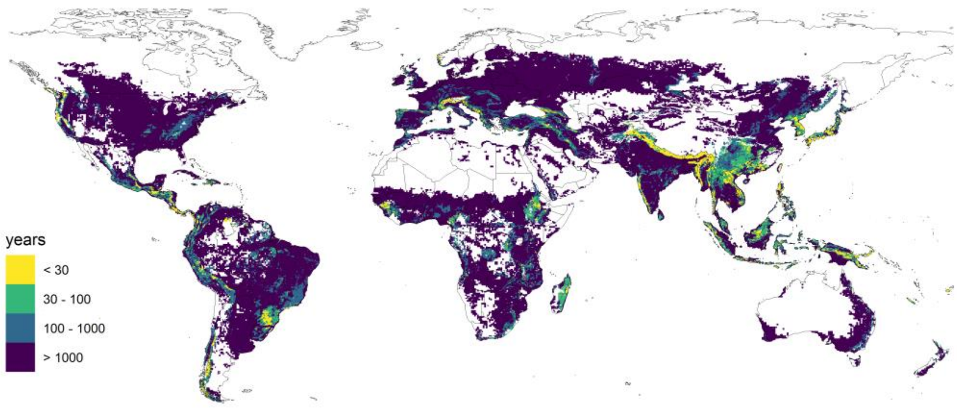


Figure 1:Simulated years left until the whole soil profile is eroded in each simulation unit. Calculated as a ratio of the sedimentary deposit thickness [m] (Pelletier et al., 2016) *and the eroded soil depth per year (water erosion [t ha^{-1} a^{-1}] x bulk density [g m^{-3}]).*

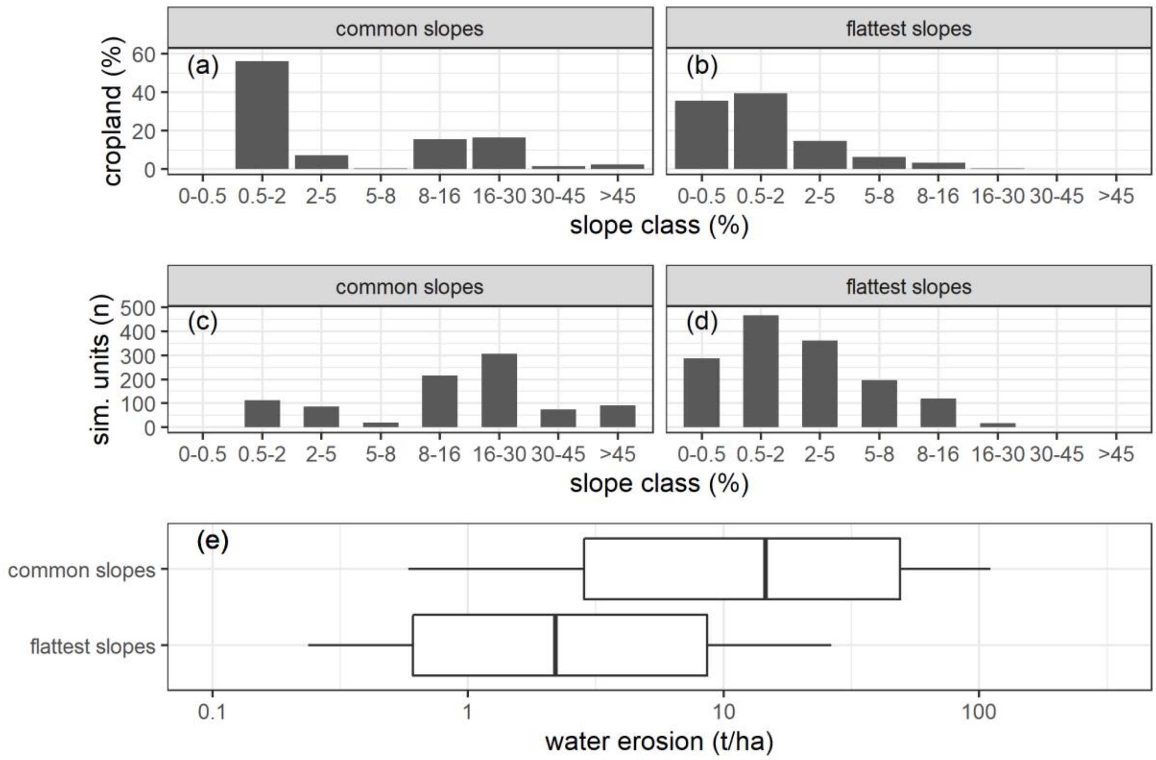


Figure 2: Comparison of slope inputs and simulated water erosion outputs between the cropland distribution scenario using the most common slopes and the cropland distribution scenario using the flattest terrain available in Italy. (a, b) distribution of the cropland share (Portmann et al., 2010) *per slope class. (c, d) distribution of simulation units per slope class. (e) Simulated water erosion for Italy using both cropland distribution scenarios. Midlines visualise median values, boxes include values from the 25th to the 75th percentiles and whiskers bracket values between the 10th and the 90th percentiles.*

Line 184-187

Again, where is the evidence that steeper slopes are actually cultivated, and on what basis are these P-factors selected? Were the parameters selected using empirical evidence, or a citation?

As described above, we cannot be certain that steep slopes are cultivated, but we assume that steep slopes are only cultivated with conservation techniques to reduce high water erosion values. The P-values for contouring and terracing are within the range of the values reported by Morgan (2005), which are presented on lines 151 -157.

We modify line 185 accordingly: "*To account for erosion control measures reducing high water erosion on steep slopes, we use a conservation P-factor of 0.5 on slopes steeper than 16 %, and a P-factor of 0.15 on slopes steeper than 30 % to simulate contouring and terracing based on the range of P-factors presented in Morgan (2005).*"

Lines 377-379

"…a significant share of the estimated soil removal of 7 Gt a-1 originates from small wheat and maize fields on steep slopes with strong annual precipitation". So here the authors admit that the global

numbers are skewed by extreme levels of simulated erosion. But more evidence that these fields actually exist needs to be provided.

See comments and discussion above about the high uncertainty in cropland distribution on steep slopes.

We delete the total soil loss value from the abstract, line 26, as it is significantly influenced by extreme water erosion rates from mountainous regions. But we will keep the value in the discussion, where we address the uncertainty of the global soil loss value.

Lines 391-392
How were the countries where "conservation agriculture… is likely" selected? What evidence is there for this?

We selected countries where conservation agriculture is most likely based on the share of conservation agriculture reported by AQUASTAT (2005-2014). The criteria is presented on lines 178-179 and table 3.

We will refer to AQUASTAT (FAO, 2016) on line 392.

Lines 423-425
That "…many older measurements are poorly accessible as they are not available online" seems to be a bit of a weak argument for not collecting more measurements on soil erosion. Can the authors elaborate a bit more in what kind of data are out there and precisely what it would take to utilize them for future studies?

Indeed, this is true. There was huge amount of erosion measurements at experimental plots in many countries. For example, in USA first measurements started in 1915 and when Wischmeier and Smith were developing their equation they had about 10000 erosion plot/year data and this was in 1970ies. These data are archived by USDA but they are not directly accessible on internet. When in Germany Schwertmann was verifying USLE for Germany he used about 2500 plot/year data, but they are not available on internet and only small part was published and it was in German. We know situation mainly in central Europe. In Slovakia we have about 50 plot/year data published in Slovak language, we know about erosion plot measurements in Hungary, a lot of old data are in Czechia (starting with measurements by Maran in 1950ies, and Poland (starting by Gerlach in 1950ties), significant data set is in Austria, whole book about long term measurements (ca 20 years) was published in Croatia in Croatian language, there was extensive measurement programme in Yugoslavia (Serbia, Gavrilovic, Djorovic,). A lot of data exists in China, Japan, UK and Russia. In Africa we know about data from Uganda and Zimbabwe, most data from Francophone Africa are in French, from Latin America in Spanish, etc. There are five major reasons why most data are not available:

1. Many older publications are in national languages
2. Many older publications are not on internet
3. Many measurements were published in grey literature, local conference proceedings, national acta of scientific institutions, unpublished reports, etc.
4. Many published data are hardly interpretable because metadata are lacking (slope lengths, or inclinations or crop cover, period of measurement is not recorded, geographical position of the sites is not recorded, many measurements were running only during vegetation period of studied crop so they do not represent annual erosion, etc.).

5. International journals do not have interest to publish usual case studies which present raw data. To get paper published the authors need to present some special objectives to follow some special goals or developing methodological innovations. Therefore, also many new data sets cannot be found online.
6. Even if paper is published, journals have usually size limitations. To save space the primary data are not presented, only the results of interpretation, statistical processing, etc. are there.

The collected data set represents a reasonable compromise to achieve the objectives of this study. It is far beyond the capacities of the team and the objectives of this study to collect all existing erosion data. Such task would require 3-5 years lasting international project with participation of research teams from most countries, so that each team would be able to revise data sources in his country and provide summary of data including those published in national language and unpublished reports.

We added a more comprehensive discussion to available field data to the response addressing the second referee.

We increased the field data sample from 473 to 606 following a comment by the second referee. We will change the values and the presentation of the field data accordingly on lines 218 – 220, 232 – 234, 312 – 314.

Criteria for the appropriate selection of field data are addressed on lines 426 – 449. We will further clarify the field data needs in the discussion after line 421: "*The main reasons for the low availability of suitable data to evaluate simulated water erosion rates are twofold: (i) erosion monitoring is expensive, time consuming and labour demanding; and, (ii) primary data and metadata of measurement sites accompanying final results are often not available and many older measurements are poorly accessible as they are not available online (Benaud et al., 2020). A variety of factors influencing water erosion such as climate, field topography, soil properties and field management need to be considered when modelling water erosion but are often not reported in available field measurements (García-Ruiz et al., 2015). This hampers a direct comparison between simulated and observed water erosion values. We demonstrated the varying match between measured and simulated water erosion using different tillage and cover crop scenarios. Metadata on field management often only provides the crop cultivated and therefore the conditions under which erosion was measured in the field are not known sufficiently to evaluate erosion values simulated under different field management scenarios. Similarly, information on field topography and soil properties is often not provided with recorded field measurements and thus their use is limited in an evaluation of water erosion estimates simulated in different global environments. Moreover, the geographical distribution of erosion data is unbalanced. Most data are concentrated in the United States, West Europe and the West Mediterranean (García-Ruiz et al., 2015). In summary, there is a lack of field data representing all needed regions, situations and scenarios (Alewell et al., 2019).*"

We will additionally mention "*the lack of sufficient metadata accompanying erosion measurements*" on line 235.

We will add two sentences comparing the high variability within field data with the deviation between simulated values and measured values based on the evaluation results to Line 331: "*Outside locations combining steep slopes and strong precipitation, median deviation between simulated and measured data is lower than the variability within the field data.*" Line 451: "*In most environments relevant for maize and wheat cultivation the deviation between simulated and measured water erosion values is lower than the variability within the field data.*"

Lines 466-467

Yes, it seems clear that increased resolution would be important. Several datasets are already available however, including 100m agricultural cover fraction data (Buchhorn et al., 2019) and 90m topography from a range of different datasets, such as MERITHydro (Yamazaki et al., 2019). Global climate and soils data are available at at least 1km resolution and could be downscaled (Fick Hijmans, 2017; Hengl et al., 2017). Some more explanation as to why the authors were limited to 5' and more concrete recommendations for future research would be valuable.

We rely on the existing data infrastructure of the EPIC-IIASA model, which has been constructed and evaluated for large-scale and global crop yield projections. The EPIC-IIASA model uses state-of-the-art global crop management and agro-environmental input data and has been positively evaluated for representing national average yields and inter-annual yield variability globally (Balkovič et al., 2014). It was used in several studies and its outputs have been compared to regional yield statistics and other global crop and land use models as a part of ISI-MIP and GGCMI model inter-comparison initiatives (Mueller et al., 2017). One of the main goals of this study is to analyse if EPIC-IIASA can account for relationships between water erosion and crop cultivation. Therefore, we rely on the existing model setup and data infrastructure of EPIC-IIASA, which has been confirmed as a reliable model to simulate daily crop growth on a global scale. The Input data for EPIC-IIASA originally available at different scales were aggregated at 5' resolution grid. In EPIC-IIASA, each simulation grid is represented by a representative field (1 to 10 hectares, depending on the prevailing slope category) while the field topography was calculated as a "dominant combination" from the high-resolution 90-m SRTM digital elevation model. Given the large uncertainty in land cover maps (Fritz et al., 2015; Lesiv et al., 2019), EPIC-IIASA does not provide an explicit link between land cover category, such as cropland, and the dominant fields. Instead, an area share of each land cover category per simulation grid is provided based on the GLC2000 land cover map with 1x1 km spatial resolution.

As mentioned above a discussion on the uncertainty in cropland distribution and slope input data will be added, as well as an explanation of the concept of the "representative field".

We will further clarify the focus of this paper in the introduction, line 83: "*The overall aim of this study is: (i) to analyse the robustness of water erosion estimates in all global agro-environmental regions simulated with an EPIC-based global-gridded crop model; and, (ii) to discuss the main drivers affecting the robustness and the uncertainty of simulated water erosion rates on a global scale.*"

We further highlight the model's weakness in conclusion line 471: "*Using existing field data, we were able to identify specific environmental characteristics for which we have lower confidence in the modelled erosion rates. These are mainly found in the tropics and mountainous regions due to the high sensitivity of simulated water erosion to slope steepness and precipitation strength, and the complexity of agricultural systems in mountainous regions.*"

Lines 473-474
As the high erosion "areas represent only a small fraction of global cropland for wheat and maize", why not show median values as the headline results instead of means?

We agree that the presentation of both mean and median values can be confusing. In the revised version we will focus only on median values. However, in the discussion, line 375 we mention both mean and median value to demonstrate the skewed distribution of erosion rates due to extreme values simulated on steep slopes.

We present global median water erosion in maize (7 t/ha) and wheat (5 t/ha) fields on line 25,244, 312 and delete average values.

Global average water erosion values simulated under different management scenarios and different water erosion equations will be deleted on line 483 – 387 to focus only on median values.

We add a row to Table 3 clarifying that the median is used to aggregate water erosion values simulated under all management scenarios for simulation units and regions.

Lines 684-689; Figure 2
I would like to see the map and statistics separated out into two, one figure set each for maize and wheat. As the growing areas are different and only partially overlapping, it would be very helpful to see these individually in the main body of the manuscript.

We will present two maps for maize and wheat respectively in the revised paper (see figure below).

We will group bars by crop in the revised version (see figure below).

The explanation that water erosion is presented as a weighted average from maize and wheat fields will be deleted in table 3.

We include a note in the figure label explaining that pixel cells in figures do not indicate cropland sizes. "*Each pixel cell illustrates the median relative water erosion of one representative field. The extent of cropland areas is not considered in pixel cell size.* "

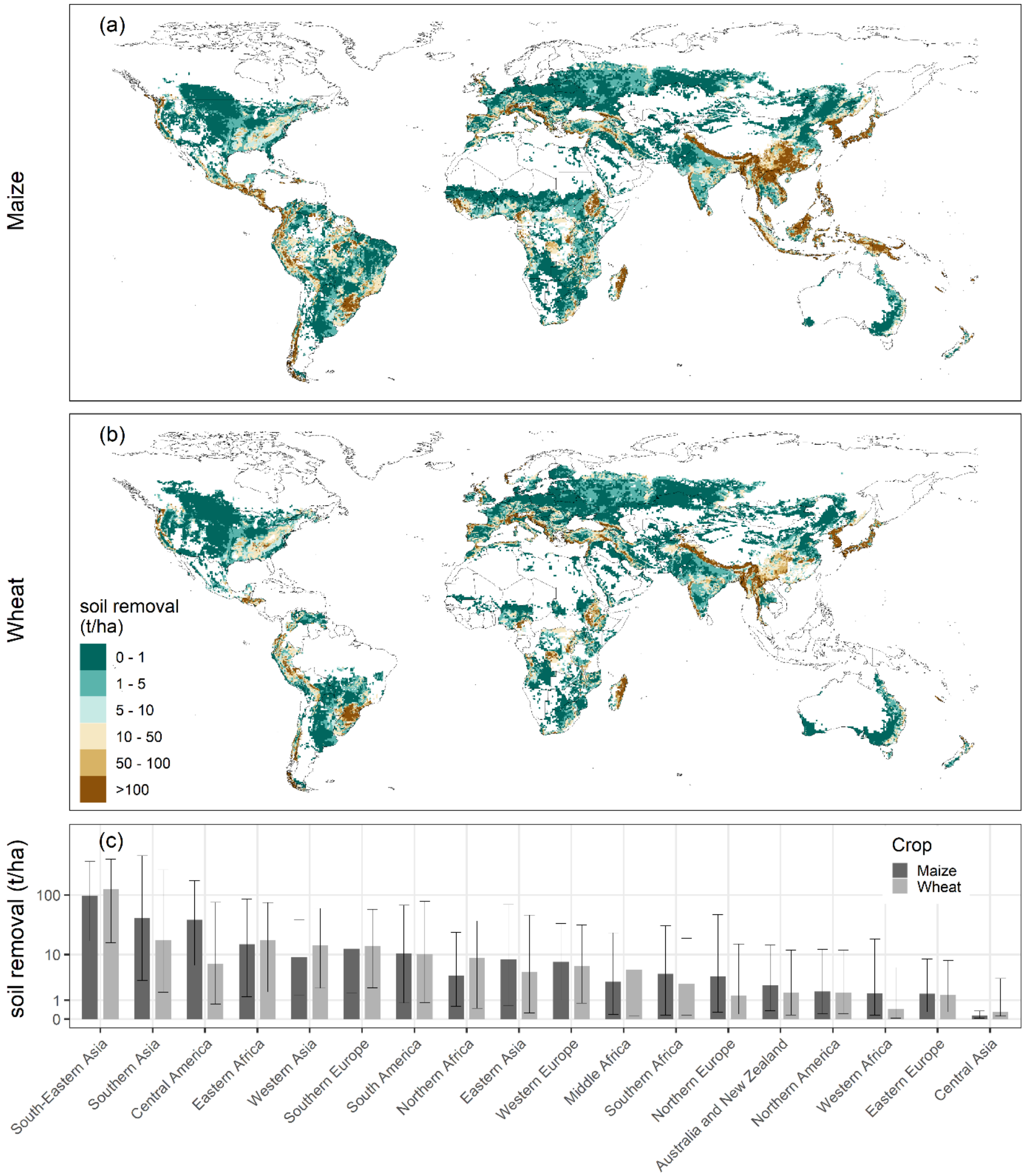


Figure 3: Soil loss due to water erosion in maize (a) and wheat (b) fields simulated with the baseline scenario. Each pixel cell illustrates the median relative water erosion of one representative field. The extent of cropland areas is not considered in pixel cell size. The bars in the bottom plot (c) illustrate median soil removal for major world regions simulated under maize and wheat cultivation. The lines and whiskers illustrate 25th and 75th percentile values. The classification of world regions is illustrated in Fig. S4. Due to the large gap between aggregated values, all values in the bottom plot have been log-transformed to facilitate the visual comparison.

Lines 706-709; Figure 7

I am quite suspicious that there is any substantial amount agriculture at all in the purple areas marked on the map, e.g., Borneo highlands, northern Laos, Himalayan front, western Madagascar, Korea, Japan. If there is, agriculture must be limited to valley *bottoms that are not detected at 5' resolution or done with extreme terracing.*

Each pixel in the maps illustrates the median erosion rate of one representative field. The pixel cells in each map do not indicate total cropland area. In other words, most of the pixel in mountainous regions represent a very small cultivated area. Table 3 lists details on how erosion rates in each pixel are aggregated.

Lines 691-693; Figures 3 and 4
Would also be useful to see how much uncertainty is caused by the assumption of what slopes are being farmed, e.g., always lowest slopes first, mean slope, median slope, etc.

We will address slope uncertainty in an extended discussion (see comments above)

References

Alewell, C., Borrelli, P., Meusburger, K., & Panagos, P. (2019). Using the USLE: Chances, challenges and limitations of soil erosion modelling. *International Soil and Water Conservation Research*, *7*(3), 203–225. https://doi.org/10.1016/j.iswcr.2019.05.004

Balkovič, J., van der Velde, M., Skalský, R., Xiong, W., Folberth, C., Khabarov, N., et al. (2014). Global wheat production potentials and management flexibility under the representative concentration pathways. *Global and Planetary Change*, *122*, 107–121. https://doi.org/10.1016/j.gloplacha.2014.08.010

Benaud, P., Anderson, K., Evans, M., Farrow, L., Glendell, M., James, M., et al. (2020). National-scale geodata describe widespread accelerated soil erosion. *Geoderma*, *371*(April), 114378. https://doi.org/10.1016/j.geoderma.2020.114378

FAO. (2016). AQUASTAT Main Database. Retrieved July 1, 2020, from http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en

Fritz, S., See, L., Mccallum, I., You, L., Bun, A., Moltchanova, E., et al. (2015). Mapping global cropland and field size. *Global Change Biology*, *21*(5), 1980–1992. https://doi.org/10.1111/gcb.12838

Lesiv, M., Laso Bayas, J. C., See, L., Duerauer, M., Dahlia, D., Durando, N., et al. (2019). Estimating the global distribution of field size using crowdsourcing. *Global Change Biology*, *25*(1), 174–186. https://doi.org/10.1111/gcb.14492

Montgomery, D. R., 2007. Soil erosion and agricultural sustainability. Proceedings of the National Academy of Sciences of the United States of America, 104(33), 13268–72.

Morgan, R. P. C. (2005). *Soil erosion and conservation* (3rd ed.). Blackwell Science Ltd.

Mueller, C., Elliott, J., Chryssanthacopoulos, J., Arneth, A., Balkovic, J., Ciais, P., et al. (2017). Global gridded crop model evaluation: Benchmarking, skills, deficiencies and implications. *Geoscientific Model Development*, *10*(4), 1403–1422. https://doi.org/10.5194/gmd-10-1403-2017

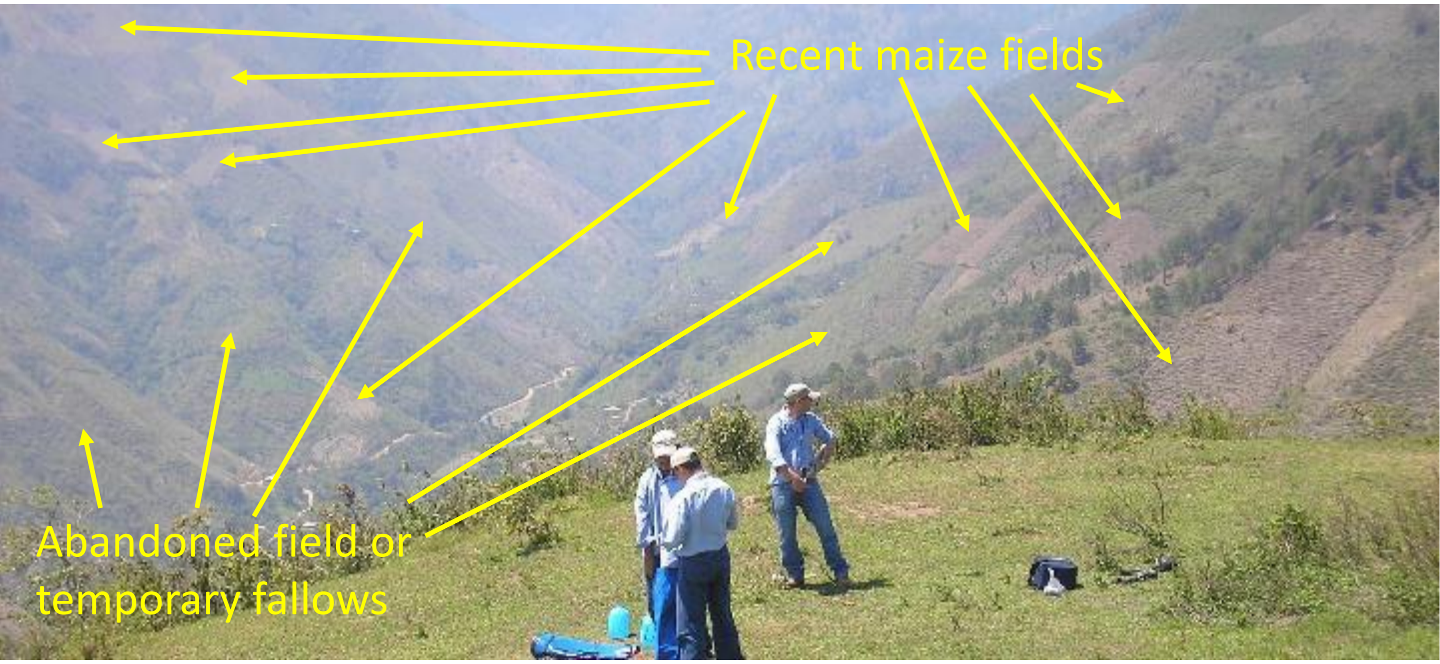
Pelletier, J. D., Broxton, P. D., Hazenberg, P., Zeng, X., Troch, P. A., Niu, G.-Y., et al. (2016). A gridded global data set of soil, intact regolith, and sedimentary deposit thicknesses for regional and global land surface modeling. *Journal of Advances in Modeling Earth Systems*, *8*(1), 41–65. https://doi.org/10.1002/2015MS000526

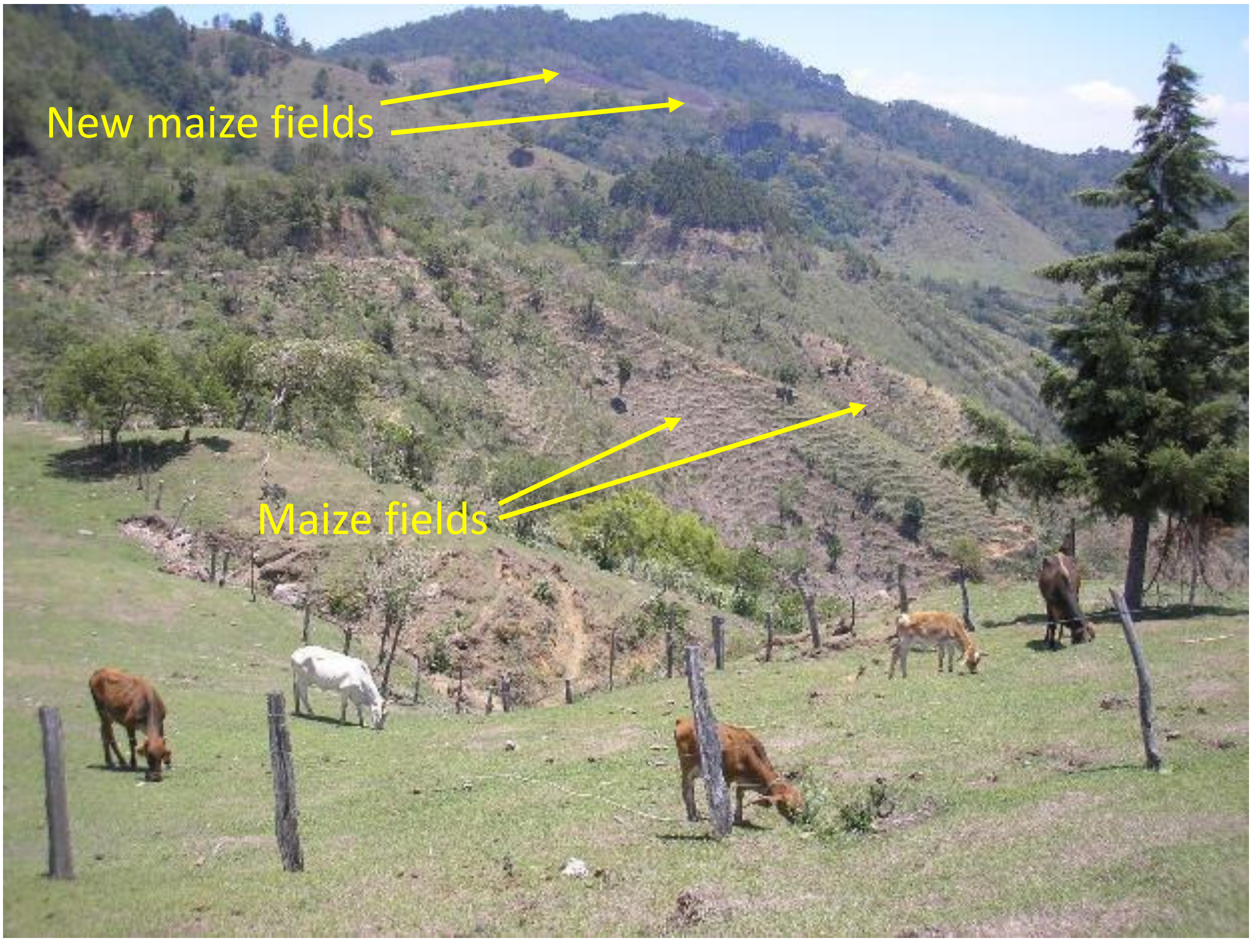
Portmann, F. T., Siebert, S., & Döll, P. (2010). MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles*, *24*(1). https://doi.org/10.1029/2008GB003435

Wischmeier, W. H., & Smith, D. D. (1978). Predicting rainfall erosion losses. *Agriculture Handbook No. 537*, (537), 285–291. https://doi.org/10.1029/TR039i002p00285

Latin America

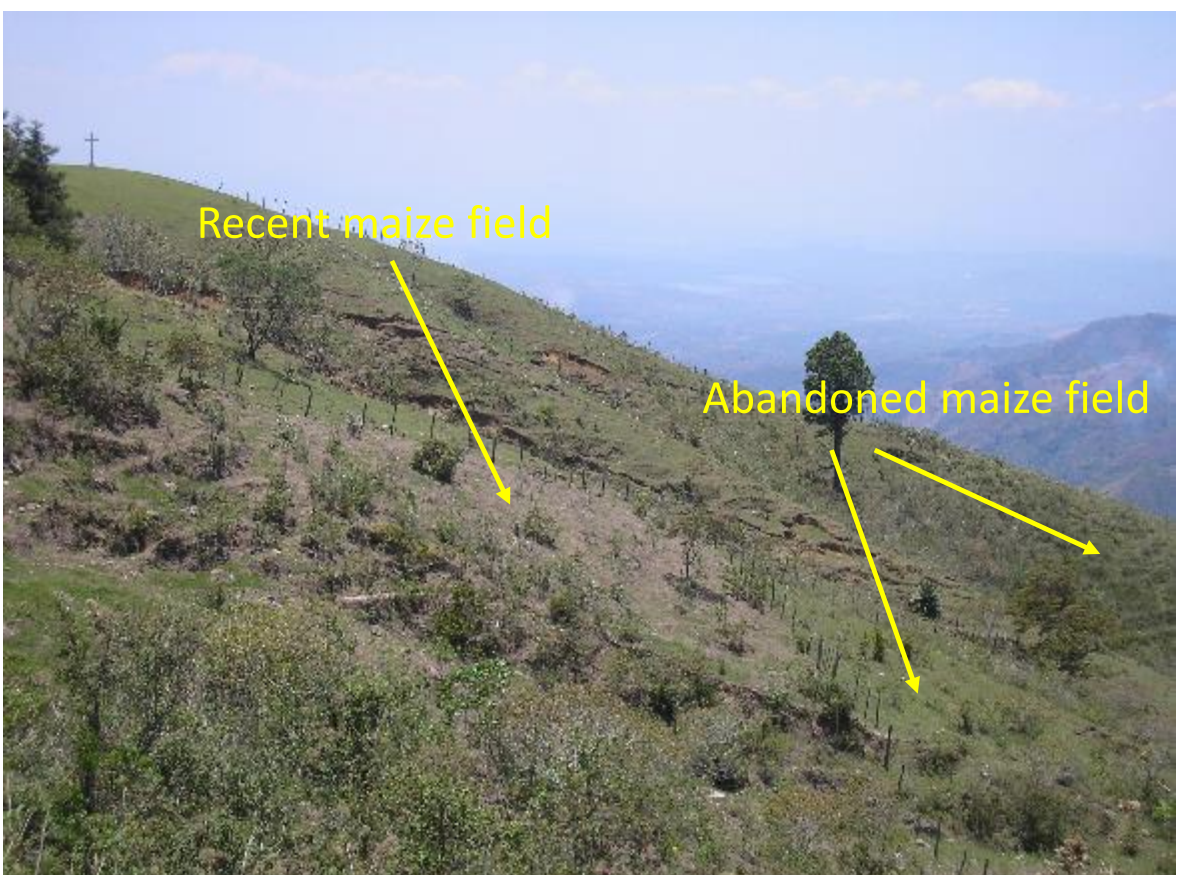
Mountain agriculture in El Salvador: Volcanic soils are fertile, climate is warm and moist, so even extremely steep slopes are cultivated. There is a lot of volcanic bombs and boulders but the cultivation is possible because they use hand labour (working with hoes). Maize is absolutely dominant crop.





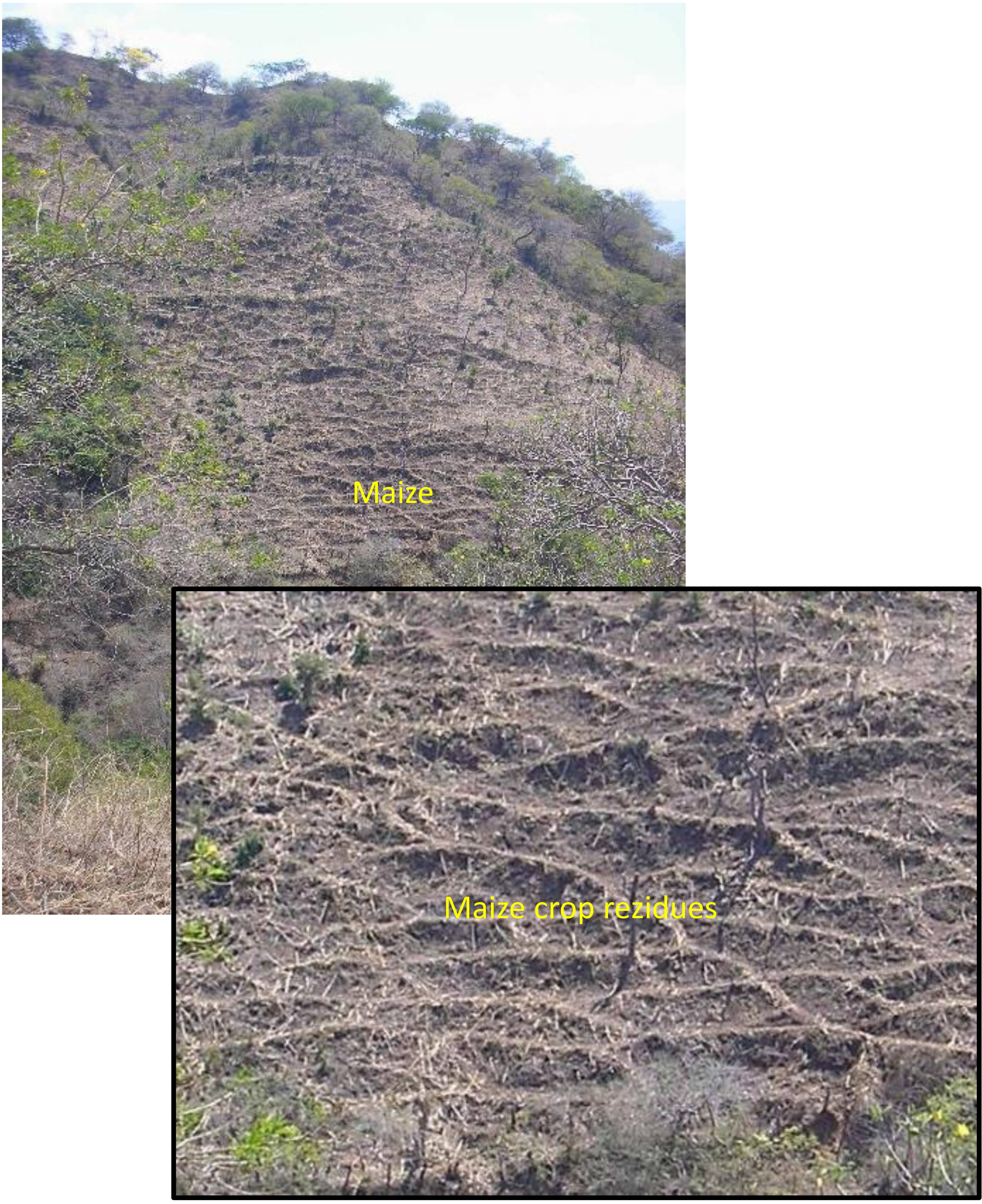
Latin America

Mountain agriculture in El Salvador



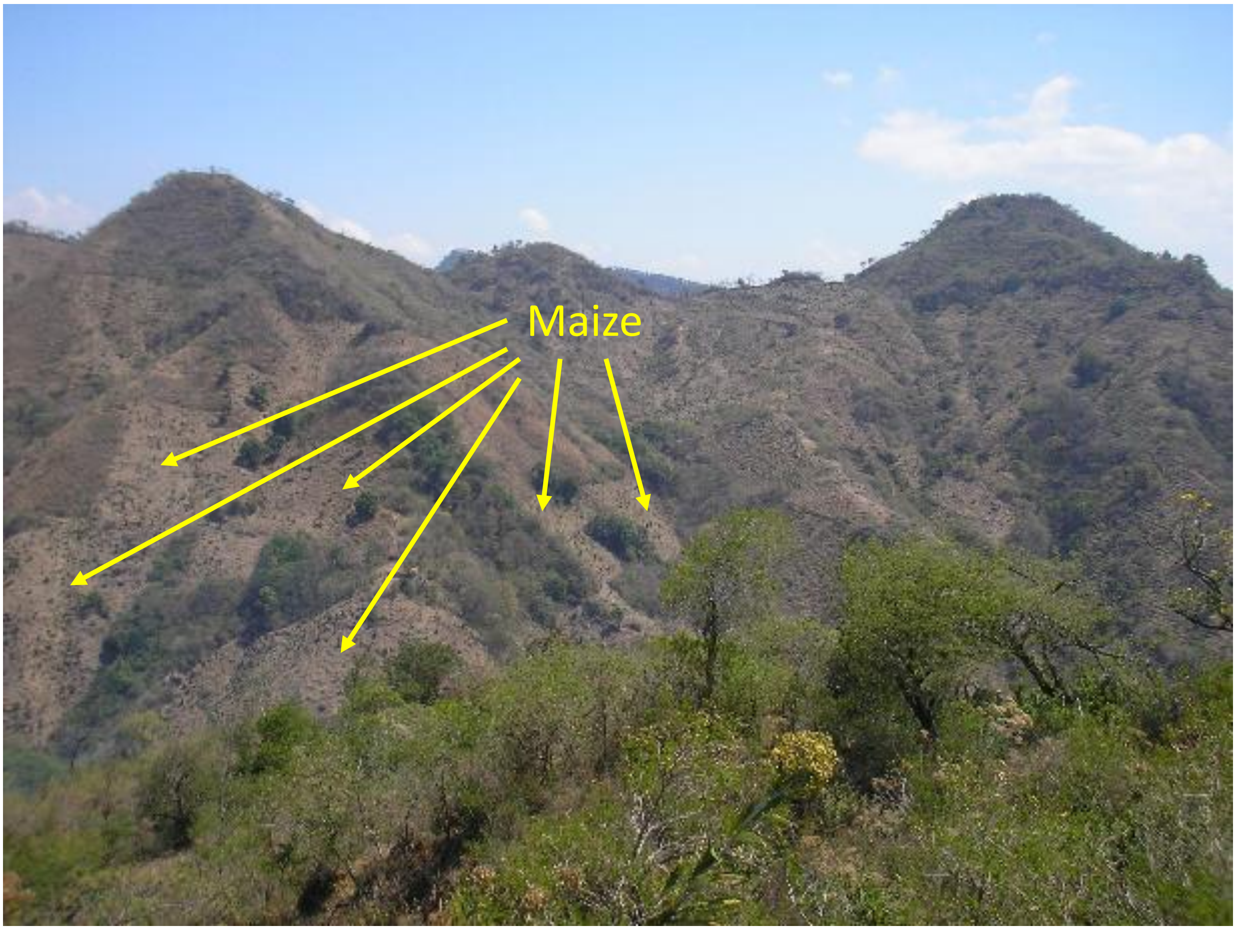
Latin America

Mountain agriculture in El Salvador: Land is used sometimes as cultivated maize fields, sometimes as pasture land (also after maize harvest there is grazing. Most slopes has dense microrelief of livestock pats and biological erosion. From distance it looks like pasture land but it is maize field. Very typical feature in El Salvador



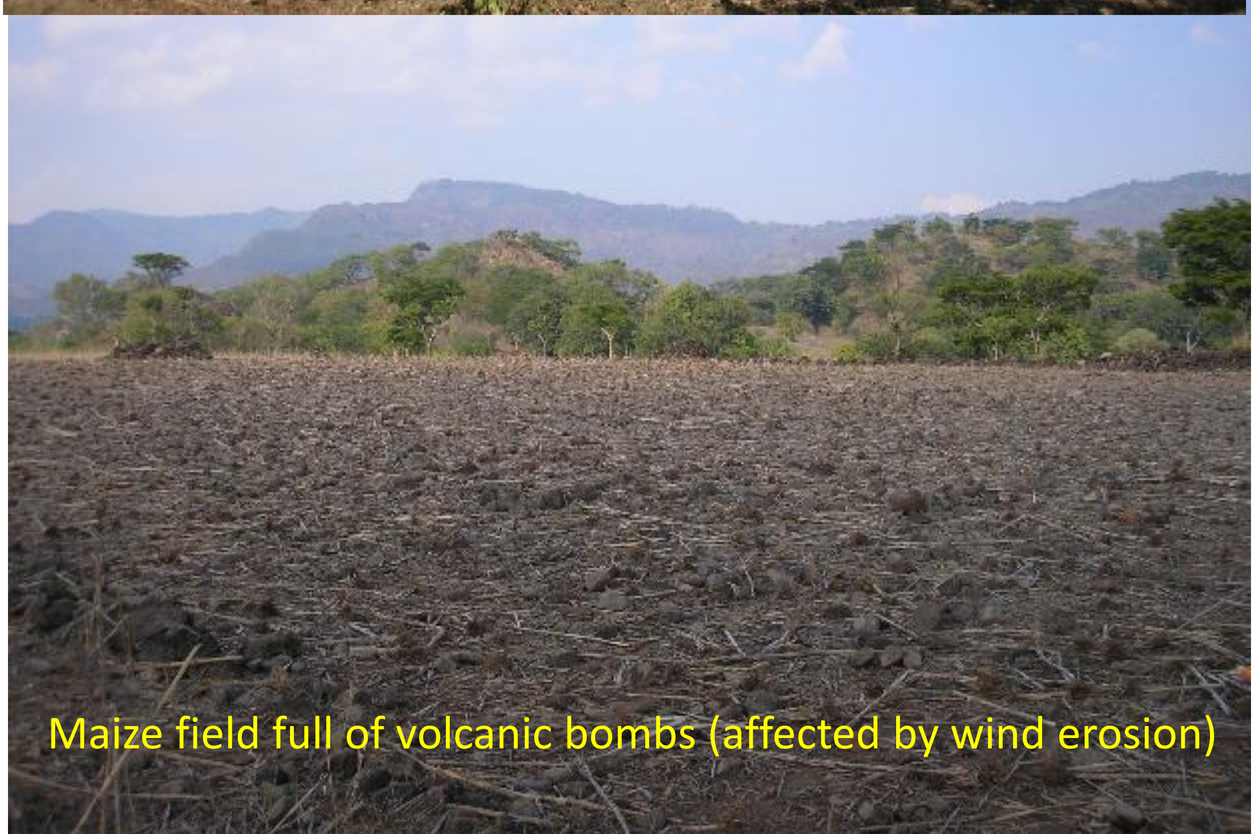
Latin America

Mountain agriculture in El Salvador



Latin America

Mountain agriculture in El Salvador

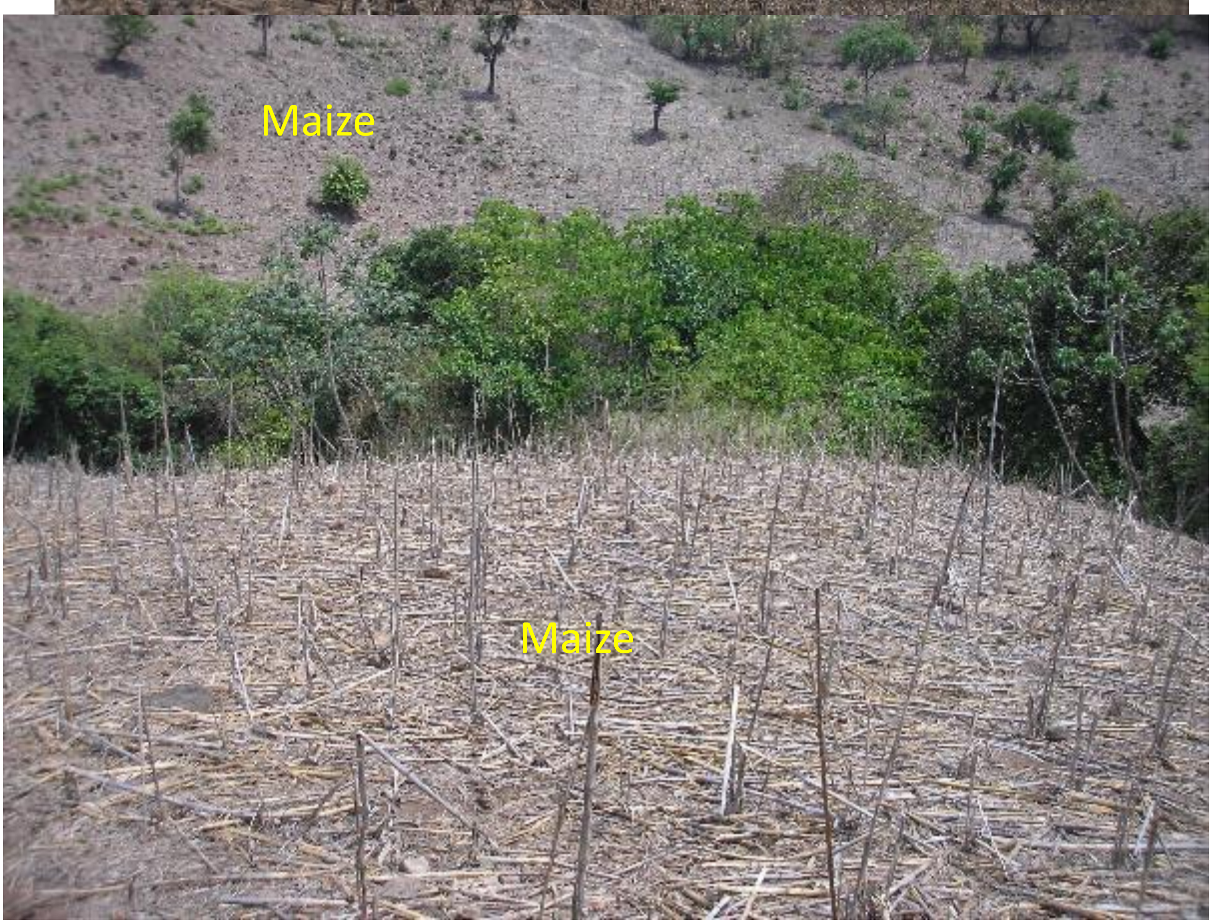


Latin America

Mountain agriculture in El Salvador

Latin America

Mountain agriculture in El Salvador



Latin America

Mountain agriculture in El Salvador

Latin America

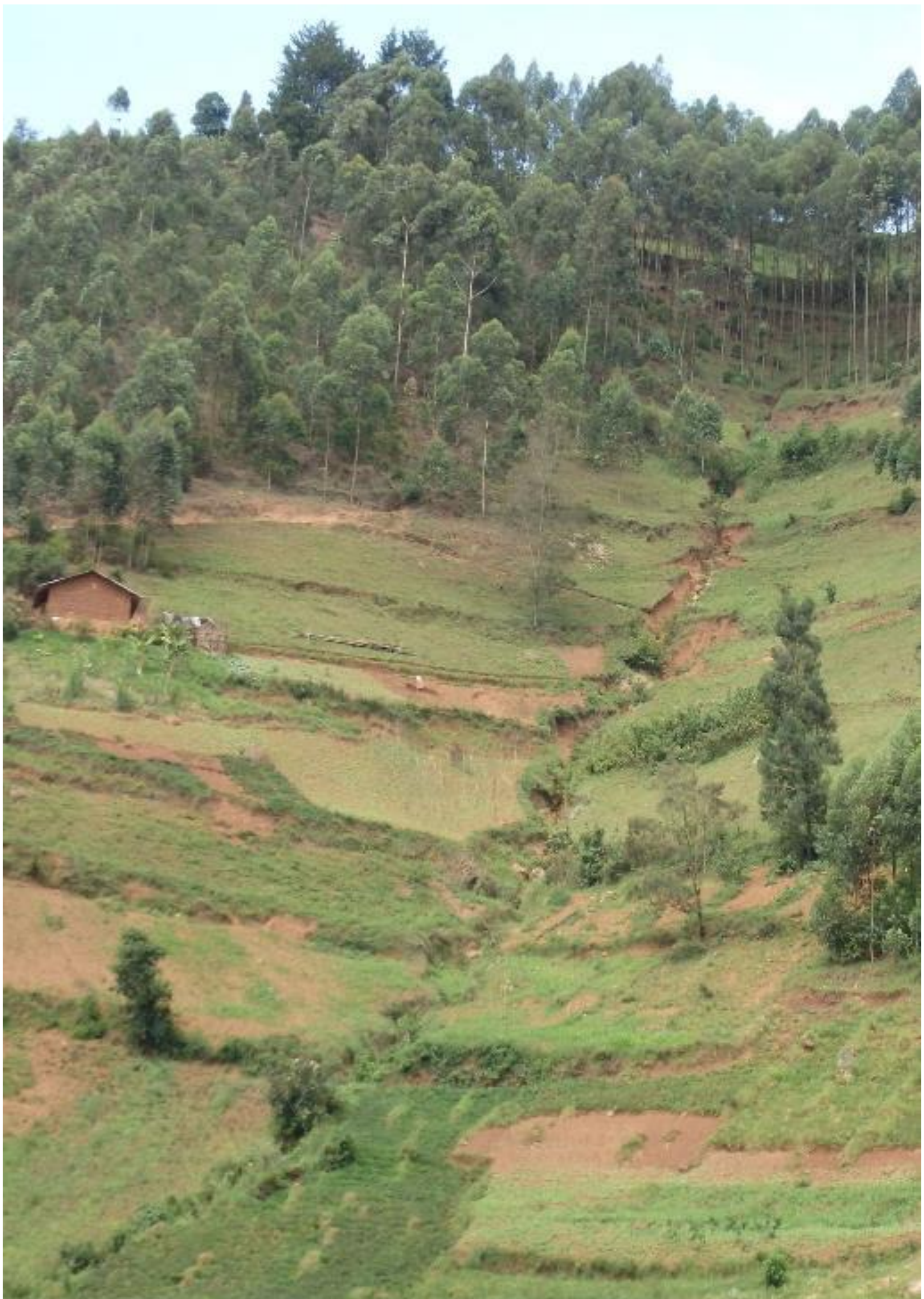
Mountain agriculture in El Salvador

Africa

Mountain agriculture in Uganda with terraces
but strongly affected by tills and gullies

Africa

The areas with young eucalyptus forests (in all next figures are extremely devastated and abandoned fields which were reforested with funding of World Bank



Africa

Mountain agriculture in Uganda

Africa

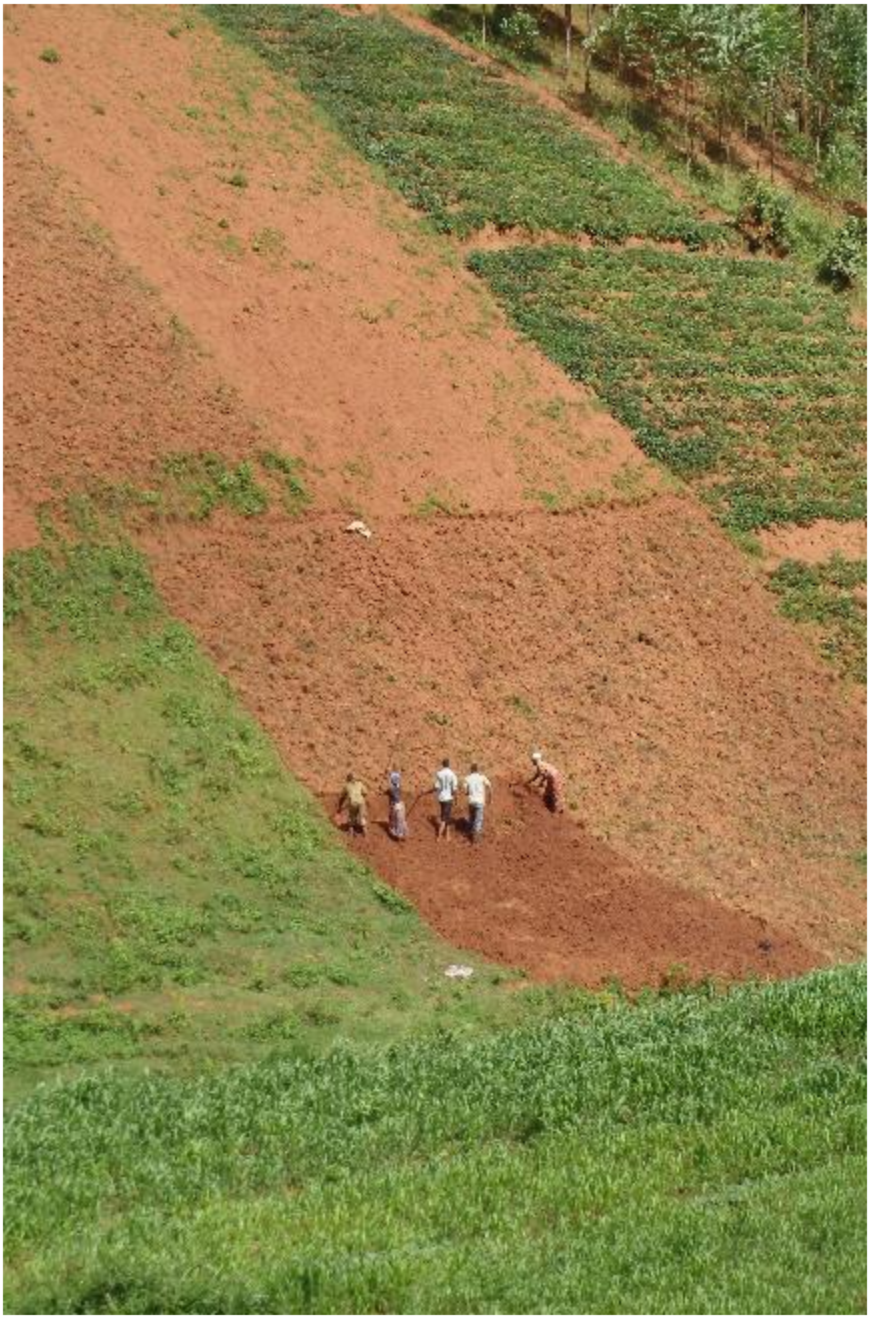
Mountain agriculture in Uganda

Africa

Mountain agriculture in Uganda

Africa

Mountain agriculture in Uganda



Africa

Mountain agriculture in Uganda

Africa

Mountain agriculture in Uganda

Africa

Mountain agriculture in Uganda: uppermost fields strongly degraded by erosion and abandoned few years ago, recently used for grazing

Africa

Mountain agriculture in Uganda: maize is common crop on slopes.

Africa

Mountain agriculture in Uganda: maize is common crop on slopes.

Africa

Mountain agriculture in Uganda: maize is common crop on slopes.

Africa

Mountain agriculture in Uganda: maize is common crop on slopes.

Africa

Mountain agriculture in Uganda: maize is common crop on slopes.

Africa

Mountain agriculture in Uganda: maize is common crop on slopes.

Africa

Mountain agriculture in Uganda: maize is common crop on slopes.

Africa

Mountain agriculture in Uganda: maize is common crop on slopes.

Africa

Mountain agriculture in Uganda: maize is common crop on slopes.

Africa

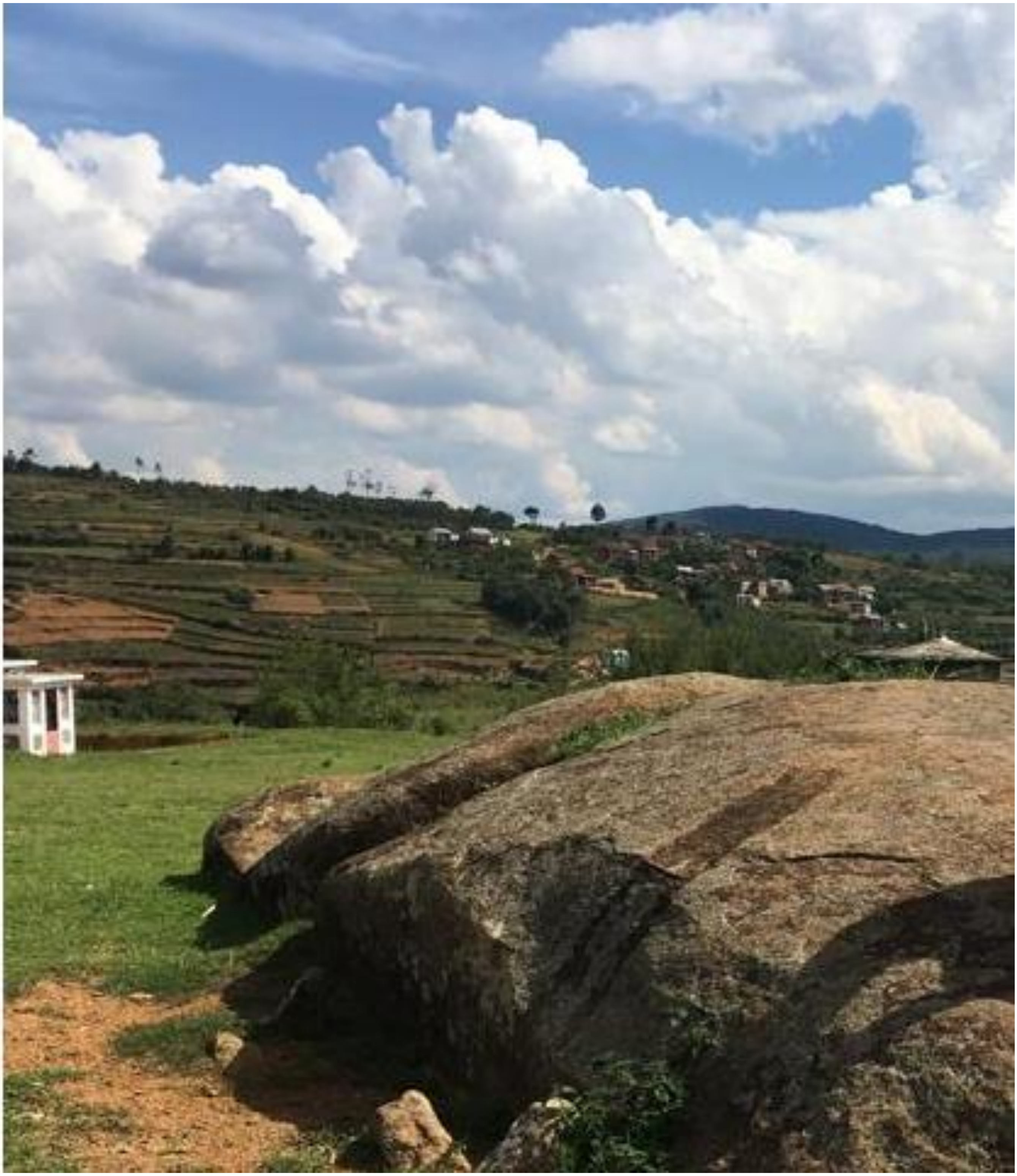
Mountain agriculture in Madagascar

Africa

Mountain agriculture in Madagascar

Africa

Mountain agriculture in Madagascar



Asia

Mountain agriculture in South China

Asia

Mountain agriculture in South China

Asia

Mountain agriculture in South China

Asia

Mountain agriculture in South China


Asia
Mountain agriculture in South China
Sheet erosion under sugar cane

Asia

Slope agriculture in Loess Plateau, Northern China

Asia

Mountain Agriculture Sri Lanka

Asia

Deforestation in Vietnam

Central Europe

Mountainous agriculture in Slovakia:

It began in 17th century but most intensive was in 19th century. Many fields were already devastated in last quarter of 19th century and first half of 20th century and farmers were migrating to America.

Completely devastated field at foot slope, recently still cultivated

Central Europe

Mountainous agriculture in Slovakia

In 17th – 19th century large areas of footslopes of Carpathians were devastated by huge gullies, recently mostly self-stabilised.

Central Europe

Mountainous agriculture in Slovakia

Recent ploughing in subsoil - dolomitic rock