were composited on a monthly basis (June to September) and four samples were analyzed for each plot during each monitoring season. The total seasonal nutrient loss through water erosion was calculated by summing the losses associated with runoff water and sediment for each plot (Fig. 3.2).

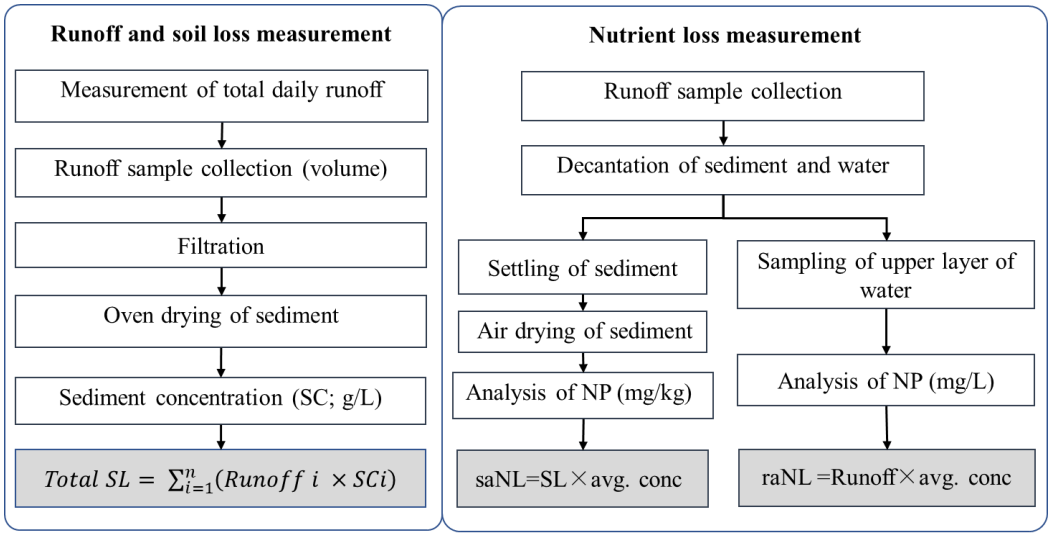

Figure 3.2. Method used to measure runoff, soil, and nutrient losses from experimental plots; SC, sediment concentration; SL, soil loss; saNL, sediment-associated nutrient loss; and raNL, runoff-associated nutrient loss.

II. Measurement of nutrient outflows associated with product harvest (*Ho*)

Removal of harvested products (grain and cropped/grazed straw/grass) are usually the major pathways of nutrient outflows, although the amount varies with crop type, soil type, management practices, and plant nutrient uptake (Brady and Weil, 2008). We measured grass biomass from GL and DBL under closed and open access conditions, and grain and straw yields of tef from CL (Fig. 3.1) using the methods listed in Table 3.2. The amounts of nitrogen and phosphorus lost via the harvest were calculated by multiplying the total amount of each biomass (grain and grass) with their N and P contents (Eqs. 3.2 and 3.3; Stoorvogel and Smaling, 1990).

$$Ho = Y \times \text{N cont.} \quad \text{(Equation 3.2)}$$

$$Ho = Y \times \text{P cont.} \quad \text{(Equation 3.3)}$$

Where *Ho* is outflow of N or P via biomass harvest (kg ha^{-1} yr^{-1}); *Y* = yield of harvested products (kg ha^{-1} yr^{-1}); and cont. = content (kg per kg of harvested product). For cropland, we considered nutrient outflow via grain harvest and crop residues both separately and together, because in the

highlands, about 80% of crop residue was removed from the fields, including at the study sites (Elias et al., 1998). For plots in both open and closed GL and for plots in closed DBL, we measured outflow of nutrients via grass biomass only; we did not calculate outflow of nutrients via grass product harvest from open DBL plots because they were almost bare during the study period.

To measure aboveground biomass of grass on exclosure/fenced GL and DBL plots and on both CL plot types, samples were harvested in a quadrat (1 m^2) at three locations (upper, middle, and lower) of each plot each year in November and sun-dried until they reached a constant weight. Dried tef samples were manually threshed, and the grain was sifted and winnowed to remove dust and other materials. Samples were weighed using a digital balance (precision = 0.001 g), and the grain and straw yield values for tef and grass values for exclosure/fenced GL and DBL plots recorded at each location were converted to kg ha^{-1} yr^{-1} and used to quantify the total nutrient loss associated with product harvest (Eqs. 3.2 and 3.3). To determine the representative grass biomass yield on control GL plots, we collected grass biomass data (three replicates) from used open grazing land near the experimental plots at 30-day intervals for each of the study sites during the rainy months (July to October in 2018 and 2019). Three locations within each plot, chosen at random by throwing the quadrat (1 m × 1 m), were sampled, cutting at 2 cm above ground level. The amount of grass removed by grazing animals was converted to kg ha^{-1} yr^{-1} as suggested by Mekuriaw et al. (a personal communication).

III. Measurement of nutrient losses associated with leaching (*Lo*)

Dissolved or soluble nutrients present in the topsoil are potentially prone to removal by leaching depending on climate (rainfall) and soil (draining) characteristics, whereas less soluble nutrients such as phosphate are less prone to loss owing to their adsorption to soil particles (Carmo et al., 2017). To calculate leaching losses, we therefore considered only TN, using a regression model developed by Stoorvogel and Smaling (1990) (Eq. 3.4).

$$Lo = 2.3 + (0.0021 + 0.0007 \times F) \times P + 0.3 \times (IN1 + IN2) - 0.1 \times TNU \quad \text{(Equation 3.4)}$$

where *Lo* = nutrient losses associated with leaching (kg N ha^{-1} yr^{-1}), *P* = mean annual rainfall (mm), *F* = soil fertility class (1 = low; 2 = moderate; 3 = high, which referred from literature), *IN1* + *IN2* = mineral fertilizer and manure applied (kg N ha^{-1} yr^{-1}) and *TNU* = total N uptake by plants (kg ha^{-1} yr^{-1}). Rainfall amount was obtained from manual and tipping-bucket rain gauges installed at each site. The amount and type of mineral fertilizer (*IN1*) applied in our experimental CL plots

was determined based on farmers interview for each site, and the total TN and P_{av} inputs were calculated by converting the total amount of fertilizer into corresponding quantities of N and P (Elias et al., 1998). Organic fertilizer (*IN2*), mainly farmyard manure, was applied in CL plots at Guder, based on the local farmer's application rate and also composited samples were taken and analyzed for N and P content. The total amount of TN and P_{av} added to the soil was determined by multiplying the dry weight of applied farmyard manure by its nutrient content (Aticho et al., 2011). On open GL and DBL plots, the quantity of animal droppings in randomly selected 25 m^2 (triplicate) quadrats near each plot were measured at weekly intervals, and annual excretion was determined by incorporating loss factors (Haileslassie et al., 2007), that is, assuming 40% of dung is lost to household energy consumption (MoA, 2002). For each month, composite samples of animal droppings were collected from each open GL and DBL plot, oven dried at 105 °C, and analyzed for N and P contents (Mohamed Saleem, 1998).

IV. Measurement of nutrient losses by gaseous emissions (*Go*)

Nitrogen loss from soils in the form of denitrification (NO, N_2O, and N_2) and volatilization (NH_3) is considered as loss by gaseous emissions (Stoorvogel and Smaling, 1990). Denitrification takes place under anaerobic conditions, although a soil does not have to be entirely saturated for denitrification to take place. Ammonia volatilization is linked to the amount of mineral and organic fertilizers applied and mainly occurs in alkaline environments; however, such soils are not very common in sub-Saharan Africa (Bouwman, 1998). Volatilization was therefore not treated separately, but in combination with denitrification (FAO, 2003). We estimated *Go* using the regression model developed by the FAO (2003) as given below (Eq. 3.5).

$$Go = (0.025 + 0.000855 \times P + 0.01725 \times Nf + 0.117 \times OC) + (0.113 \times Nf) \quad \text{(Equation 3.5)}$$

where *Go* is nutrient losses in gaseous form (kg N ha^{-1} yr^{-1}), *OC* is soil organic carbon content (%), *P* is mean annual rainfall (mm), and *Nf* is the sum of mineral and organic fertilizer N (kg N ha^{-1} $year^{-1}$).

Table 3.2. Summary of variables measured and methods used to quantify TN and P_{av} losses via four nutrient outflow processes.

Outflow	Nutrients	Variables	Methods of quantification
Water erosion (*Eo*)	TN and P_{av}	Daily rainfall, runoff volume, sediment yield, nutrient content of runoff, and sediment samples	Field measurement and lab. analysis
Product harvest (*Ho*)	TN and P_{av}	Grain and straw/grass yield, nutrient content of grain, and straw/grass	Field measurement and lab. analysis
Leaching (*Lo*)	TN	Average annual rainfall, N input from mineral and organic fertilizers, SOC, plant N uptake, and animal droppings on open grazing fields	Stoorvogel and Smaling, 1990
Gaseous emissions (*Go*)	TN	Average annual rainfall, N inputs from mineral and organic fertilizer, and SOC	FAO, 2003

TN, soil total nitrogen; P_{av}, soil available phosphorus; SOC, soil organic carbon.

3.2.4 Soil, runoff, and plant sampling and laboratory analysis

To estimate soil nutrient losses, post-harvest soil samples (0–20 cm) were collected by hand auger at three locations (upper, middle, and lower) of each plot in both study years (n = 108; 3 samples per plot × 6 plots per site × 2 years × 3 sites) and analyzed for different parameters: texture, pH, soil organic carbon (SOC), TN, and P_{av}. Dry bulk density, soil moisture, and water infiltration were also determined for each plot (Table 2.3).

Composited liquid water samples (n = 120; [4 samples per plot in each rainy season × 6 plots per site × 2 years × 2 sites] + [4 samples per plot × 6 plots per site × 1 year for Dibatie]) and corresponding composited sediment samples (n = 120) were analyzed for their TN and P_{av} contents using the standard procedures detailed in Table 2.3.

Figure 3.3. (a) Runoff volume and colour difference on cropland plots with (right) and without (left) soil bunds; (b) decanted samples of runoff water for runoff-associated nutrient loss analysis, and (c) filtered and air-dried sediment samples for sediment-associated nutrient loss analysis.

Samples for analysis of the N and P contents of grass biomass, grain crop yield, and crop residue, were prepared at Bahir Dar University the Soil Laboratory. A total of 120 samples were analyzed using standard procedures (Table 2.3).

3.2.5 Estimating costs of nutrient losses

To assess the costs of soil nutrient losses, a 'replacement cost' approach (Bojö, 1996) was applied. This approach calculates the loss of nutrients and estimates its economic value based on the cost of an equivalent amount of commercial fertilizers. The current local price of inorganic fertilizer was used to estimate costs. The cost of the total P_{av} loss was calculated by converting to an equivalent amount of P_2O_5 ($P_2O_5 = P_{av} \times 2.29$) and then to nitrogen, phosphorus, and sulfur (NPS) fertilizer. Similarly, the TN (additional to the applied NPS), was calculated by using the cost of urea fertilizer, common in our study sites.

3.2.6 Statistical analysis

Depending on the distribution of the data, parametric or non-parametric inferential statistical tests were used to evaluate the degree of variability in soil nutrient losses among agro-ecological zones, land use types, and SLM practices. Analysis of variance (ANOVA) was performed, and means were separated using the least significant difference test ($p < 0.05$) for nutrient losses by product harvest, leaching, and gaseous emissions among agro-ecological zones and land use types; variation in water erosion–associated nutrient loss was evaluated using the Kruskal–Wallis test, a non-parametric test that performs well with non-normally distributed data. Correlations among measured parameters were determined following Pearson's method (Gomez and Gomez, 1984). Statistical analyses were carried out with Microsoft Excel 2016 and SPSS 23.0 software (SPSS Inc., Chicago, IL, USA).

3.3 Results and Discussion

3.3.1 Variation of soil nutrient outflows across agro-ecological zones

Nutrient losses associated with water erosion (*Eo*), product harvest (*Ho*), leaching (*Lo*), and gaseous emissions (*Go*) observed during the two study seasons in different agro-ecological zones are presented in Table 3.3. Across the 18 plots in the three agro-ecological zones, the two-year average value of TN loss ranged from 39.6 to 55.5 kg ha^{-1} yr^{-1}, whereas P_{av} loss ranged from 4.1 to 5.9 kg ha^{-1} yr^{-1}. TN loss increased in the order Dibatie (lowland) < Aba Gerima (midland) <