Impacts of Land Use Change on Soil Erosion and Water Quality—A Case Study from Hawaii

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Abstract: The ongoing diversification of agricultural lands in Hawaii to replace sugarcane and pineapple plantations is a major challenge. It presents an interesting case study for global concerns with land degradation-land use interaction. The important question posed by this paper is: ***will "diversified" crops have a different impact on the natural resource base and environmental quality from earlier cropping systems?*** We used the revised universal soil loss equation (RUSLE) to examine a number of scenarios toward an answer to this question. Our quantitative predictions showed that annual crops grown with "conventional" practices would be considerably less protective against sediment losses than sugarcane. Orchards and short rotation bio-energy (fuel tree) plantings are also vulnerable during the early stages of tree growth, after full canopy, and during or following harvest or logging operations. Well-managed pastures represent a highly "protective" alternative. Similar arguments are made for impacts on contamination of surface and groundwater supplies by agrichemicals. Biological soil conservation options offer substantial promise for protecting soil and water quality under vulnerable land uses.

1 Introduction

Land use change is a very important aspect of "global change". This is because it is often induced by changes in population trends and economic environments, and can be intimately linked to other forms of change, including changes in climate, biological diversity, and accelerated land degradation. In Hawaii, plantation agriculture was, and to some extent remains, the dominant means of sugarcane and pineapple production. "Diversified" agriculture, particularly in replacement of sugarcane, is on the rise. Because of the high rainfall erosion potential in these tropical islands (El-Swaify, 1999 and Hawaii CZMP, 1996), we hypothesize that agricultural diversification will have very profound impacts on the sustainability of Hawaii's natural resource base and environmental quality. This paper addresses this hypothesis.

2 Erosion trends in plantation crops

As a reference point for this analysis, we use data obtained from long-term erosion assessments in representative agricultural watersheds. The studies related runoff and sediment losses to rainfall, soils, land use, and commonly-practiced field management. Five small watersheds ranging in size from 0.8 to 2.8 ha were selected and fully instrumented for continuous monitoring of rainfall, runoff, and sediment loss (El-Swaify and Cooley, 1980) . A summary of the results is shown in Table 1.

Table 1 Sediment loss logs for agricultural watersheds during the monitoring period*

Watershed name (area, Ha)	Elevation (m)	Soil name (Taxonomy)	Median annual rainfall (mm)	Prevailing slope %	Primary cropping	Recorded mean annual EI_{30} Tonne m /Ha/Yr	Monitoring period, months	Mean annual soil loss (Mg/ha/yr)
Laupahoe-hoe (0.9)	509	Kaiwiki (Typic Hydrandept)	3556	16	Sugarcane	739	60	1.18
Honokaa (2.2)	492	Kukaiau (Hydric Dystrandept)	1981	17	Sugarcane	166	78	2.37
Waialua 1 (2.5)	287	Paaloa (Humoxic Tropohumult)	1448	10	Sugarcane	139	109	2.52
Waialua 2 (0.8)	308	Wahiawa (Tropeptic Eutrustox)	1092	6	Pineapple	276	53	7.02
Kunia (2.9)	305	Kolekole (Ostoxic Humitropept)	864	7	Pineapple	180	122	7.13

* Additional details on the characteristics of these watersheds were provided by El-Swaify and Cooley (1980) and El-Swaify (1999).

All the soils in the study were well drained and considered to have low to moderate erodibility.

A close look at cropping history showed, as expected, that the majority of soil loss occurred when the soils were left bare between crop plantings or as plantation roads. The measured sediment losses did not reflect the substantial amount of soil movement that occurred within the watersheds; significant redeposition of sediments removed from the steeper slopes occurred in the more level areas. The low mean soil loss for the Waialua (S) watershed (Ultisol) reflected the low annual rainfall and total erosivity (EI_{30}) values over the monitoring period. For the purpose of the present analysis, three important conclusions were drawn from the monitoring study:

- Rates of soil loss from watersheds were highly variable from year to year, but were lower than the acknowledged maximum soil loss tolerances used in conservation planning. This is because both crops are effectively managed as virtual "perennials", with ratooning that involves few periods of soil "disturbance" or exposure and leads to adequate soil protection "within planted field areas".
- Only a few storm events that coincide with soil exposure are responsible for the majority of soil losses. Therefore, the timing of "disturbance" in field operations and maximum soil cover within certain periods of the year is a very important determinant of erosion vulnerability and should be a strong component of conservation planning
- The high percentage of plantation roads is responsible for the higher and sustained erosion rates under pineapple culture. Better planning of such access roads is important for reducing sediment losses from agricultural lands.

3 Predicting outcomes of land use diversification

The "diversified" crops that are likely to replace plantation crops may be annuals, orchards, or pastures. Their impacts on erosion and nonpoint pollution are expected to be as diverse as the specific crops that are selected, and the management practices applied to them. This is because of variations in planting density, planting geometry, timing of various critical operations, the duration and attributes of various crop growth stages (including ratooning strategies where applicable), and the use of protective erosion control structures or land surface configurations. Since "conservation tillage" is not a common practice in Hawaii, an important element for the purpose of comparison with former plantation crops is the frequency and timing of soil "exposure" and "disturbance" due tillage, field preparation, and crop harvest operations.

The Revised Universal Soil Loss Equation (RUSLE) is a useful model for predicting and evaluating these impacts. The equation has the form:

$$A = R\,K\,S\,L\,C\,P \qquad (1)$$

In which A = predicted soil loss, R = rainfall erosivity, K = soil erodibility, S and L are factors dependent on slope steepness and length, C = crop management factor, and P = land management practices factor. Therefore, C is the *primary soil protection variable that is associated with diversification* because it allows comparing the protective attributes of alternative cropping systems. C, in turn, may be defined as:

$$C = PLU*CAN*SR*ROOT*ROUGH \qquad (2)$$

The right-hand-side terms in equation 2 are "subfactors" representing *prior land use, crop canopy cover, surface residue cover, plant roots in the upper soil layer, and soil surface roughness, respectively.* Inherently, C is a dynamic function that also depends on rainfall distribution within the year and the timing of various field operations.

To apply RUSLE, we derived rainfall erosivity values from our iso-erodent maps for Hawaii (Lo, 1982), soil erodibility values from our direct measurements or predictive equations for important agricultural soils (El-Swaify and Dangler, 1977), published values for topographic parameters (Renard *et al*., 1996), and C values from "*soil loss ratios*" based on our direct measurements or derived from other published data. Soil exposure and disturbance periods result in higher s*oil loss ratios* than do periods with ample soil protection.

4 Results

We applied RUSLE model predictions to a variety of diversification scenarios in the Pearl Harbor Watershed on the island of Oahu, where major land use conversions from plantation sugarcane are taking place. The soils in the case study are primarily Oxisols, with an erodibility of 0.20, receive an average rainfall of 900 mm, occur on an average slope gradient of 9% and with average slope length is 30 m. It is assumed that crop planting cycles begin at the onset of the rainy (fall) season. The scenarios are for "infield areas", i.e. they do not consider changes in the percent or orientation of plantation roads as may be necessary for the replacement crops.

Scenario 1: Upland taro, with conventional tillage, as a replacement crop for sugarcane—The Bunlong (Chinese) variety of taro is grown in Hawaii for processing as chips. It has a 9 month cycle. When planted at a density of 6 plants/m^2 it achieves a maximum canopy cover after 125 days. Leaf residue is sparse and decomposes rapidly, and so provides only temporary and minimal soil surface protection against erosion. Thus, in contrast to the sediment losses reported above (Table 1) for sugarcane (range 1.2 to 2.5 Mg/(ha • yr)); the model predicted a 100% increase in the C-factor and subsequent soil loss for upland taro, ranging from 2.4 to 5.0 Mg/(ha • yr).

Scenario 2: Bulb onions, with conventional tillage, as a replacement crop for sugarcane—Bulb onions are grown on a 130 day cycle. The crop never provides full soil surface cover because of the distinctive canopy structure. It produces little or no surface residue. Two to three crop cycles can be grown in a single year, with a corresponding number of soil exposures and disturbances. These facts suggest that it poses a relatively high erosion hazard. In contrast to the sediment losses from sugarcane reported above in Table 1, we predicted a 220% increase in the C-factor and subsequent soil loss, providing a range from 3.8 to 8.0 Mg/(ha • yr) for bulb onions.

Scenario 3: Taro and bulb onions, grown under the same conditions as above, but with cover pre-cropping or recycled residue as may be expected with "conservation tillage"—At each planting, 100% initial residue cover is assumed, and appropriate rates of residue decomposition are taken into account. The outcome of improved soil protection is a reduced C factor to 35% for taro and 42% for onions as compared to the values for sugarcane. Predicted soil losses are 0.41 to 0.88 Mg/(ha • yr) for taro and 0.51 to 1.1 Mg/(ha • yr) for onions.

Scenario 4: Orchards or short rotation bio-energy plantings—Both of these alternative uses are vulnerable to large soil losses during the highly exposed early stages of tree growth, after full canopy development shades out ground cover or other understory vegetation, and during or following harvest operations. No quantitative generalization can be made here because the outcome of this scenario is both commodity- and site-specific; and is highly dependent on the employed planting density and selected methods for weed control, harvest or logging operations, and other applied practices.

Scenario 5: Conversion to pastures for animal grazing—This change can result in either accelerating soil loss or in imparting a high degree of soil protection, depending on the management used by the farmer/rancher. For example deliberate management by well-planned animal stocking rates and well-timed rotational grazing can be a most protective land use alternative in regions with a high erosion hazard.

5 Discussion and conclusions

Replacing plantation crops, especially sugarcane, with "diversified" crops will have profound impacts on both the soil resource base and water/environmental quality. The specific impact depends on the selected land use system, location, and applied management practices. Short rotation annuals are the most vulnerable systems to accelerated erosion. Similar arguments may be made for the agrochemical contamination hazards associated with diversifying land use because alternative land uses differ in their requirements and application frequencies of fertilizers and pesticides.

Among the many available soil conservation technologies, biological options should be given high preference for protecting soil and water quality (e.g. El-Swaify *et al.*, 1988). In addition, residue recycling should be promoted aggressively as it remains the single most promising but least utilized technology for soil protection in Hawaii (El-Swaify, 1999).

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