LAND DEGRADATION & DEVELOPMENT
Land Degrad. Develop. (2013)

EROSION POTENTIAL UNDER *MICONIA CALVESCENS* STANDS ON THE ISLAND OF HAWAIʻI

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Received: 1 June 2011; Revised: 3 December 2012; Accepted: 12 December 2012

ABSTRACT

This study provides evidence that *Miconia calvescens* has the potential to accelerate surface erosion in stands where it invades by (i) reducing under-canopy light levels, thereby reducing the establishment of ground cover vegetation, and (ii) producing highly erosive throughfall drops on large leaves in a single-layer canopy. The throughfall energy in a stand of invasive miconia on the Island of Hawaiʻi (USA), assessed by measuring the drop size and drop velocity distributions with a laser disdrometer, was significantly higher than that in a stand of native **ʻōhiʻa** (*Metrosideros polymorpha*) and ambient rainfall. Median throughfall drop size for miconia (3·83 mm) was twice that of ambient rainfall (1·62 mm). Highly erosive throughfall resulted from large drops forming on large miconia leaves and relatively high fall velocities associated with the single-story miconia canopy. In contrast, multi-storied natural **ʻōhiʻa** had a larger median drop size; however, a lower fall height reduced throughfall effective kinetic energy. Furthermore, the effective kinetic energy for miconia was high because large drops (> 3·8 mm) with high kinetic energy accounted for 60 per cent of the total energy (versus 30–40 per cent for other vegetation types). Consequently, unit kinetic energy of throughfall was 28 J m^{-2} mm^{-1} under miconia, compared with <24 J m^{-2} mm^{-1} for rainfall and <20 J m^{-2} mm^{-1} under **ʻōhiʻa**. These data, combined with the observation of limited protective ground cover under miconia, show the potential for accelerated erosion occurring on forest floors in stands of invasive miconia. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS: alien plant invasion; splash detachment; accelerated erosion; throughfall

INTRODUCTION

Introduced plants and animals have severely damaged native species and terrestrial ecosystems on tropical oceanic islands, including Hawaiʻi (Denslow, 2003; Meyer, 2004; Loope, 2011). The neotropical tree species *Miconia calvescens* DC (Melastomataceae), introduced as an ornamental in French Polynesia (1937), Hawaiʻi (1961), northeastern Australia (1960s), and New Caledonia (1970s) is now a highly invasive species in these environments (Fosberg, 1992; Meyer, 1996; Meyer and Florence, 1996; Medeiros *et al*., 1997; Mueller-Dombois and Fosberg, 1998; Whittaker, 1998; Murphy *et al*., 2008; Loope, 2009; Goarant and Meyer, 2010). Miconia is considered the worst invasive plant in Pacific Island wet forests (Meyer, 2004).

Miconia was first introduced Hawaiʻi in 1961 near Hilo and Onomea, both windward coastal communities on the Island of Hawaiʻi. The spread of the plant on the island was not noticed until the early-1970s, but it is now widely dispersed along the windward coast of the island (Figure 1). Miconia is now also found on three other Hawaiian islands: Maui, Oʻahu, and Kauaʻi. Thus far, monotypic stands such as those found in Tahiti are localized, found mostly in steep-sided ravines near Onomea. Spread has been limited in part by the efforts of local invasive species committees attempting to eradicate miconia. Nevertheless, miconia remains highly invasive in native forests with annual precipitation exceeding 1800 mm.

In addition to the ecological consequences of miconia invasion, anecdotal evidence suggests the replacement of native tree species with miconia may also contribute to land degradation via accelerated erosion (Meyer, 1994; Motooka *et al*., 2003). Miconia often forms dense monotypic stands with little protective ground cover vegetation (Medeiros *et al*., 1997; Figure 2). Its litter decomposes more rapidly than that of native species (Allison and Vitousek, 2004), exposing the soil surface to the direct impact of throughfall drops. Throughfall is the fraction of rainfall that falls directly through the canopy or drips from the canopy following interception by the leaves. Throughfall drops tend to be larger than rainfall drops, especially for large-leaf trees. If falling unimpeded from a sufficient height, larger throughfall drops will attain greater kinetic energy than raindrops falling from the cloud base.

The large, dark leaves of miconia reduce light levels beneath the canopy, thereby inhibiting germination and growth of understory plant species that would typically dissipate the erosive energy of throughfall drops (Meyer, 1994, 2004). The throughfall of any large-leaf species is of concern because the kinetic energy of drops falling from single-story canopies can exceed critical soil erosion thresholds (Hall and Calder, 1993; Nanko *et al*., 2008a). Direct drop impacts can compact unprotected soil surfaces and cause

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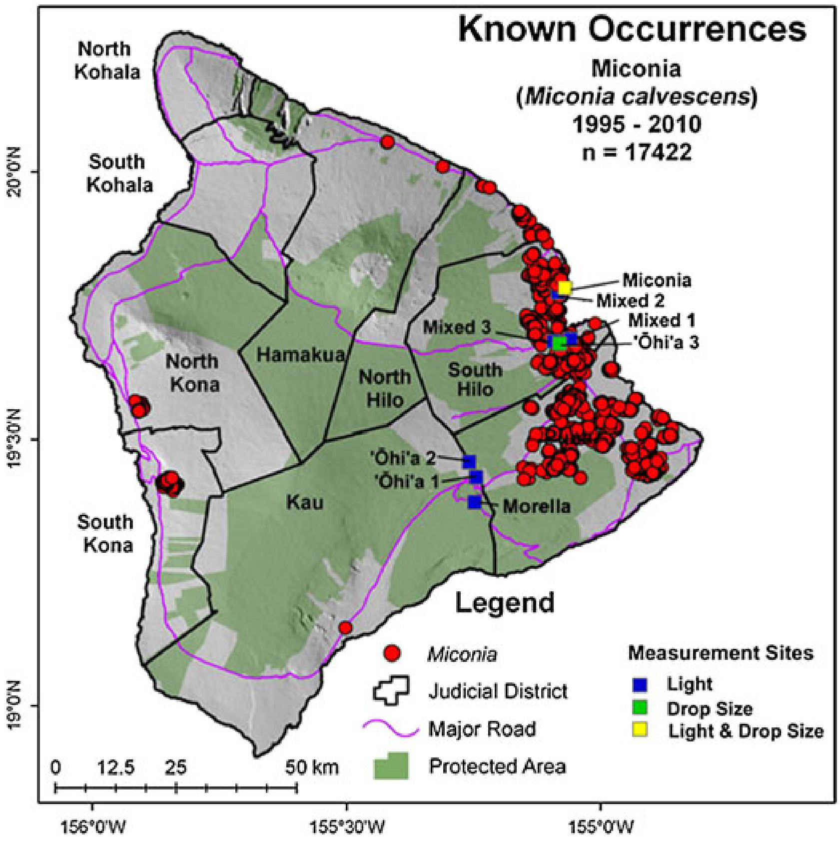

Figure 1. Miconia invasion areas on the Big Island of Hawai‘i. Also shown are study sites where under-canopy light transmission and/or throughfall measurements were made (Tables I and II). The Miconia 1 site is in Onomea, one of the locations of the miconia introduction in Hawai‘i in 1961. Base map, including locations of miconia occurrences, was provided by the Big Island Invasive Species Committee. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Figure 2. Soil surface under a miconia stand in Onomea, Hawai‘i. The high degree of root exposure suggests that several centimeters of soil have been removed since this stand was developed. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

aggregate disintegration and subsequent detachment of smaller particles that may lead to surface pore infilling. Mechanical compaction and filling of macro-pores with fines can create infiltration-reducing soil seals that increase the potential for erosive surface overland flow (Morgan, 2005; Nanko *et al*., 2008a; Nanko *et al*., 2010).

In this work, we attempt to verify the linkage between miconia invasion and accelerated erosion in Hawai‘i. At several sites, we measure canopy light transmission to ascertain the degree to which miconia reduces understory light levels; and we examine throughfall drop characteristics to quantify the erosive energy of throughfall in miconia stands. When possible, both measurements were compared with those of other types of vegetation, for example, native **‘ōhi‘a** (*Metrosideros polymorpha*) forest and other invaded forest stands with different species composition.

MATERIALS AND METHODS

Study Area

The study sites were located near Hilo and near Volcano, on the eastern part of the Island of Hawai‘i (Figure 1). We sought field study sites where miconia-dominant stands were adjacent to other vegetation (preferably native) that could serve as controls (Figure 1). However, the few accessible areas where miconia was sufficiently dense were located in areas with otherwise highly disturbed environments with relatively few native plants. Selection of the sites was geared toward measuring representative mature stands for each vegetation type. Miconia in Hawai‘i is often found in otherwise disturbed areas, limiting opportunities for side-by-side comparisons with intact native forest (**‘ōhi‘a**). In addition, because of the aggressive efforts to eradicate or contain the invasion, few accessible sites with large miconia trees were identified. Ultimately, seven sites were used for light transmission measurements (Table I) and three sites for drop size and velocity measurements (Table II).

Light Transmission and Ground Cover Measurements

A Sunfleck Ceptometer (Decagon, Pullman, WA, USA) was used to measure light transmission through vegetation canopies. Photosynthetically active radiation (PAR; μmol $m^{-2} s^{-1}$) was measured beneath the canopy within each study site. At each measurement point, the linear light sensor array of the ceptometer was held at about 1 m above the ground and moved radially, stopping to record a sample at 10 positions. The mean of the 10 readings was taken as the under-canopy light sample for that point (PAR_{below}). Approximately 10 points were sampled in this manner at each site and normalized by PAR measurements taken simultaneously in the open (PAR_{open}), which were recorded at a 1-min interval. Light transmission ratio (LTR) was calculated as follows:

$$LTR = \frac{PAR_{\mathrm{below}}}{PAR_{\mathrm{open}}} \tag{1}$$

Although quantitative measurements of live ground cover and litter were not done in this study, we made qualitative assessments on the basis of visual observations and photographs.

Rainfall and Throughfall Drop Energy

Drop size diameter and velocity of rainfall and throughfall were measured using the laser disdrometers described by Nanko *et al.* (2006, 2008a) (Figure 3C). These devices register a voltage drop when a raindrop passes between the laser source and receiver. Disdrometers were situated 0·3 m above the ground surface. The sampling area of the disdrometers was approximately 800–1000 mm^2. A splash screen was placed underneath, halfway to the surface, to prevent back splatter from drops striking the ground. Rainfall rate and depth were calculated from cumulative drop volume per time and area. A tipping-bucket raingauge (Texas Electronics model 525®, Dallas, TX, USA) was also used to measure rainfall in the open during each event.

Three rainfall events were measured between 18 and 22 December 2007 (Table III). Throughfall was monitored in miconia stands without understories (I_1); in native stands of **‘ōhi‘a** without understories (N_3); and in native stands of **‘ōhi‘a** with understories of *Psidium cattleianum* and *Melastoma candidum* (N_4). Open rainfall and throughfall were simultaneously measured with three laser disdrometers: one for open rainfall and two for throughfall. Data were aggregated into 10-min intervals for analysis.

Estimating Kinetic Energy of Drops

The kinetic energy of a raindrop (*e*; J) was calculated as (Nanko *et al.*, 2008a)

$$e = \frac{1}{2}\rho \cdot \left(\frac{\pi}{6}D^3\right) \cdot v^2 \tag{2}$$

Where: D is the equivalent spheroid drop diameter (mm); *v* is the drop velocity ($m\,s^{-1}$); and *ρ* is raindrop density

Table I. Light transmission ratio of native (N), invaded mixed (M), and invaded monotypic (I) stands

Type	Site	Composition	Canopy height (m)	*n*	LTR ± SD	COV
N_1	**‘ōhi‘a** 1	**‘ōhi‘a**	14–18	22	0·056 ± 0·020	0·36
N_2	**‘ōhi‘a** 2	Tree fern, **‘ōhi‘a**	4–15	17	0·024 ± 0·016	0·67
M_1	Mixed 1	Mixed	8–15	5	0·051 ± 0·012	0·24
M_2	Mixed 2	Mixed	15–25	10	0·026 ± 0·012	0·46
M_3	Mixed 3	Mixed	5–8	7	0·042 ± 0·008	0·19
I_1	Miconia	*Miconia calvescens*	3–8	10	0·025 ± 0·007	0·28
I_2	Morella	*Morella faya*	14–18	19	0·013 ± 0·005	0·38

The types are the following: N_1 is *Metrosideros polymorpha*. *Cibotium* spp. tree fern sub-canopy, diverse understory; N_2 is *Cibotium* spp. tree fern, *M. polymorpha*, and *Cheirodendron* sp. emergents. Fallen ferns create light gaps; M_1 is *Trema* sp., *Psidium cattleianum*, *Melastoma candidum*; M_2 is *Spathodea campanulata*, *Archontophoenix alexandrae*, *Miconia calvescens*, *Mangifera indica*. *Cyathea cooperi* understory; M_3 is *Psidium cattleianum*, *Melastoma candidum* (immature stand); I_1 is *M. calvescens*-dominated canopy. *Cyathea cooperi* understory; I_2 is *Morella faya* (monotypic stand). Canopy heights are approximated; *n* is the number of light samples taken; LTR ± 1 SD is the light transmission ratio (Equation 1); COV is the coefficient of variation of LTR.

Table II. Characteristics of throughfall study sites on the Big Island of Hawai‘i

Type	Site	Dominant species	Understory	Elevation (m)	Maximum tree height (m)	Height of the lowest branches (m)	Observation dates (2007)
I_1	Miconia	*Miconia calvescens*	No	75	8·5	5·2	18–19 Dec
N_3	**‘ōhi‘a** 3	**‘ōhi‘a**	No	108	5·0	4·0	20–21 Dec
N_4	**‘ōhi‘a** 3	**‘ōhi‘a**	*Psidium cattleianum*, *Melastoma candidum*	108	5·0	2·4	21–22 Dec

Type refers to stand type; I_1 refers to an invasive stand (Table I); and N_3 and N_4 refer to native stands.

Figure 3. (A) Canopy of an **‘ōhi‘a** tree at site N_3; (B) canopy of miconia stand at site I_1; (C) disdrometer and understory of **‘ōhi‘a** stand N_3; and (D) understory of the miconia stand I_1. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Table III. Rainfall, drop size, and kinetic energy information for three sites

		Rainfall			Raindrops				Kinetic energy			
Plot	Site	Depth (mm)	RI_{max} (mm 10-min^{-1})	RI_{mean} (mm 10-min^{-1})	Count (cm^{-2})	D_{50} (mm)	D_{90} (mm)	D_{max} (mm)	KE (J m^{-2})	KE_{N} (J m^{-2} mm^{-1})	Fraction of $KE_{0\mathrm{a}}$ (%)	Fraction of $KE_{0\mathrm{b}}$ (%)
Rf	I_1	16·3	4·7	0·3	16,280	1·62	2·39	3·38	295·4	18·2	42	0
	N_3	14·8	2·0	0·3	30,514	1·08	1·76	3·80	171·3	11·5	15	0
	N_4	33·9	5·7	0·8	42,028	1·38	2·14	3·13	534·1	15·7	26	0
Tf	I_1	5·7	2·2	0·1	2844	3·83	5·87	6·68	161·2	28·1	89	60
	N_3	8·5	0·8	0·2	8770	2·02	5·37	6·45	168·9	19·8	73	41
	N_4	19·5	3·4	0·4	3543	4·28	5·77	6·53	320·4	16·5	91	31

Note: Plot refers to either rainfall (Rf) or throughfall (Tf) at sites I_1, N_3, or N_4 (Table II; Figure 1); Depth is total event rainfall or throughfall; RI_{max} is the maximum rainfall intensity; RI_{mean} is the mean rainfall intensity; Count is the total number of drops per cm^2 during the event; D_{50} is the median drop diameter; D_{90} is the drop diameter at the 90th percentile; D_{max} is the maximum drop diameter; KE is total kinetic energy (Equation 3); KE_{N} is normalized unit kinetic energy (Equation 4); and fractions of $KE_{0\mathrm{a}}$ and $KE_{0\mathrm{b}}$ represent the portion of total effective kinetic energy associated with drops >2 mm (0·1 mJ) and 3·8 mm (1 mJ), respectively (from Equation 5).

(998 kg m^{-3} at 20°C). Total kinetic energy (KE; J m^{-2}) was calculated as

$$KE = \frac{1}{A}\cdot\sum_{i=1}^{n} e_i \tag{3}$$

Where: A is the sampling area of the disdrometer (m^2); n is the number of drops over a given period; and e_i is the kinetic energy of each drop (from Equation 2). Normalized unit kinetic energy (KE_{N}; J m^{-2} mm^{-1}) was calculated as

$$KE_{\mathrm{N}} = \frac{1}{P}\cdot KE \tag{4}$$

Where: P is event precipitation determined by summing the volume of all measured rain drops.

Effective kinetic energy (KE_0; J m^{-2}), which is an estimate of the energy associated with drops having high potential for causing splash detachment, was calculated as follows:

$$KE_0 = \frac{1}{A}\cdot\sum_{i=1}^{m}(e_i - e_0) \quad \text{for} \quad e_i > e_0 \tag{5}$$

Where: m is the number of drops with kinetic energy exceeding e_0, which is the threshold kinetic energy that must be exceeded for erosion to occur (cf. Sharma *et al.*, 1995; Salles *et al.*, 2000; Kinnell, 2005; Wakiyama *et al.*, 2010).

Previous studies found kinetic energy thresholds of less than 1 mJ (summarized in Salles *et al.*, 2000). Sharma *et al.* (1995) estimated the range of threshold kinetic energy to be 0·05–0·28 mJ using 33 cropland soils. Herein, we consider two kinetic energy thresholds: e_a (0·1 mJ) and e_b (1 mJ). These levels are associated with 2·0- and 3·8-mm-diameter raindrops, respectively, falling at terminal velocity. Thus, the effective kinetic energies are calculated for e_a (KE_{0a}) and e_b (KE_{0b}) that represent thresholds after which erosion is likely to occur.

Time-integrated kinetic energy (KE_{time}; J m^{-2} h^{-1}) can be calculated from rainfall intensity (*RI*; mm h^{-1}) and normarized unit kinetic energy.

$$KE_{\text{time}} = KE_{\text{N}} \cdot RI \tag{6}$$

For open rainfall, KE_{N} has been estimated from empirical data (Kinnell, 1980):

$$KE_{\text{N}} = e_{\max}[1 - a\exp(-b \cdot RI)] \tag{7}$$

Where: $e_{\max}$ denotes maximum unit kinetic energy (J m^{-2} mm^{-1}), and *a* and *b* are empirical constants. In general, rainfall with higher intensity has larger raindrop size distribution (e.g., Marshall and Palmer, 1948), and the larger drops have higher falling velocity (e.g., Atlas *et al.*, 1973). However, unit kinetic energy has an upper limit because raindrop size in open rainfall also has an upper limit. The review of van Dijk *et al.* (2002) reported a general $e_{\max}$ value of 28·3 J m^{-2} mm^{-1}. However, $e_{\max}$ will vary among storm types, with warm frontal rainfall, orographic rainfall, and drizzle all having lower values than cold frontal rainfall and thunderstorms.

RESULTS

Light Transmission and Ground Cover

Miconia had among the lowest LTRs of the seven stands tested in this study (Table I). However, light transmission was highly variable from point to point within some stands, as indicated by the large coefficients of variation (COV). While LTR at the **ʻōhiʻa** 2 stand was slightly lower than that of the miconia stand, COV values show that light levels were much more variable under native forest compared with miconia where LTR was uniformly low. As high-light-intensity sunflecks often penetrate the canopy in native forest in Hawaiʻi (Cordell and Goldstein, 1999), our data suggest that canopy gaps are much less numerous in miconia stands—a situation that likely inhibits the growth of erosion-mitigating ground cover. Live understory vegetation and litter densely cover the ground at native forest sites (e.g., Figure 3C), whereas the soil is almost entirely exposed with bared roots under miconia (e.g., Figures 2 and 3D); also see Figure 2 in Giambelluca *et al.*, 2010). At ceptometer measurement points within the miconia stand at Onomea, visual assessments of live understory coverage corresponded closely with variations in measured light transmission, that is, locations with the lowest light transmission were associated with little live ground cover.

The sparseness of live ground cover under miconia is exacerbated by a lack of litter accumulation. Note that LTR is even lower under *Morella faya* than miconia. This invasive tree similarly inhibits ground cover vegetation, but generally maintains a significant litter layer (Loh, 2004). As is evident in Figure 3D, leaf litter was minimal in the miconia stand. By comparison, accumulated fine litter biomass at native **ʻōhiʻa** forest site N_1 was 1·8 kg m^{-2} and exhibited an average depth of approximately 10 cm on the forest floor (unpublished data). Leaf litter decay rates are known to be quite low in native forests in Hawaiʻi in comparison with those found in invaded ecosystems (Allison and Vitousek, 2004). For **ʻōhiʻa**, the exponential litter decay coefficient, *K*, ranges from 0·22 y^{-1} (for mean annual precipitation = 500 mm) to 1·06 y^{-1} (for mean annual precipitation = 5000 mm; Austin and Vitousek, 2000). In comparison, *K* was 4·9 y^{-1} for miconia (Allison and Vitousek, 2004). Rapid litter decomposition exposes the soil surface to direct throughfall drop impact with high kinetic energy.

Open Rainfall Kinetic Energy

Precipitation totals derived from disdrometer measurements were 16·3, 14·8, and 33·9 mm (14·2, 12·7, and 30·4 mm based on the tipping-bucket raingauge) for the monitored events at sites I_1, N_3, and N_4, respectively (Table III). Data from the National Climatic Data Center (NCDC) 30-year daily rainfall archive recorded Hilo Airport, from which the three observation sites are all within 11 km, suggest that these events are typical. For example, NCDC data show that median daily rainfall is 5·1 mm, with rain days representing 75 per cent of the annual total. Days with precipitation <20 and 35 mm comprise 40 and 57 per cent of the mean annual rainfall depth, and 85 and 93 per cent of the total annual rain days.

Total kinetic energy of open rainfall during the monitored event was 295, 171, and 534 J m^{-2} at sites I_1, N_3, and N_4, respectively (Table III). Site N_4 had the largest total kinetic energy due to higher gross rainfall (33·9 mm). Although total rainfall was similar at I_1 and N_3 (16·3 vs 14·8 mm), site I_1 had 1·72 times as much kinetic energy because the drop size was greater.

Calculated unit kinetic energy increased with rainfall intensity to a limit at approximately 24 J m^{-2} mm^{-1} (Figure 4). The variables $e_{\max}$, *a*, and *b* determined from Equation 7 by a nonlinear least-squares method were 19·6, 0·76, and 0·13, respectively. This value for $e_{\max}$ is lower than that calculated in a prior work (23·7 J m^{-2} mm^{-1}) by van Dijk *et al.* (2002); based on data of Blanchard (1953). Our value may be an underestimate because it is based on a narrower range of rainfall (0–35 mm h^{-1}) than in the prior study (0–127 mm h^{-1}). Thus, we use $e_{\max}$ = 23·7 J m^{-2} mm^{-1}; and *a* and *b* are 0·73 and 0·065, respectively. The estimated KE_{N} of open rainfall during monitored events ranged from about 14·7 to 23·7 J m^{-2} mm^{-1} for intensities between 10 and 100 mm h^{-1}.

Throughfall Kinetic Energy

Throughfall depth and total kinetic energy were lower than open rainfall because of interception loss from the canopy

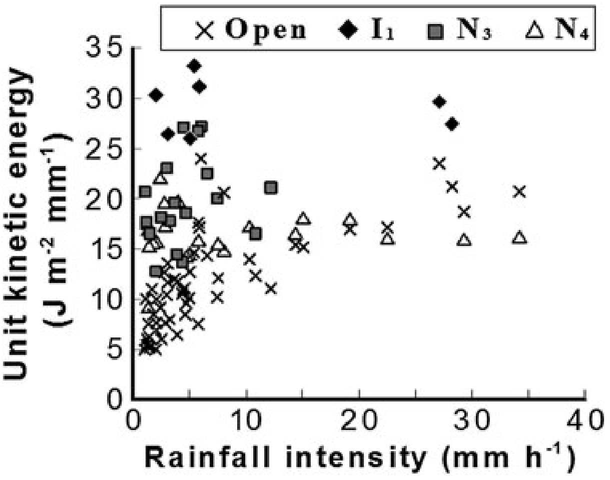

Figure 4. Unit kinetic energy related to rainfall intensity calculated from 10-min interval datasets. A scatter plot showing the relationship between rainfall intensity and kinetic energies of open rainfall with throughfall at three sites.

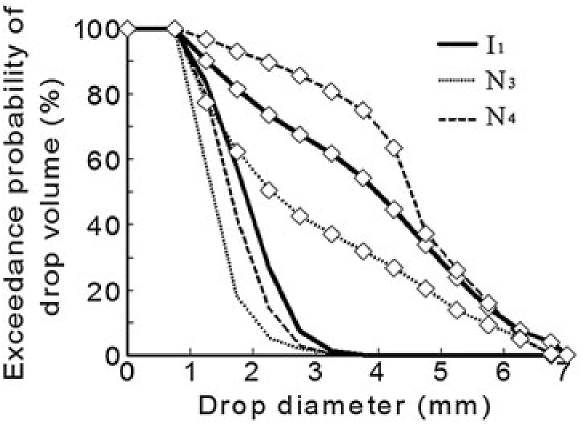

Figure 5. Exceedance probability of drop diameters determined at observation sites I_1, N_3, and N_4 (Table II). Lines with symbols refer to throughfall; those without symbols, rainfall.

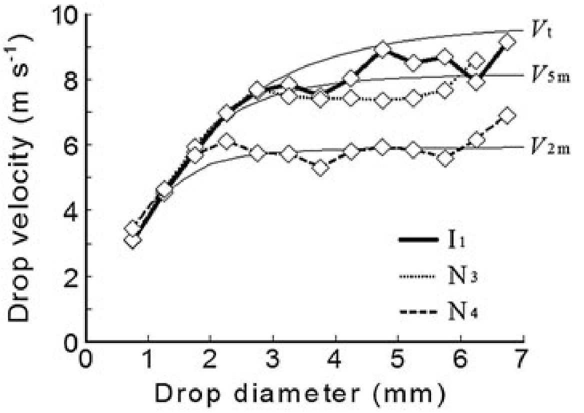

Figure 6. Mean drop velocities for various drop diameters, based on data collected at sites I_1, N_3, and N_4 (Table II). The solid lines represent terminal velocity (V_t) and velocity for drops falling from heights of 2 m (V_{2m}) and 5 m (V_{5m}) (from Zhou *et al.*, 2002).

surface and rainwater partitioning to the stemflow. Throughfall was 35, 57, and 58 per cent of open rainfall at sites I_1, N_3, and N_4, respectively; and throughfall total kinetic energy percentage was 55, 99, and 60 per cent of open rainfall. Normalized unit kinetic energy (KE_N) of throughfall was higher than that of rainfall at all sites (Table III). In particular, KE_N ($28{\cdot}1\,\mathrm{J\,m^{-2}\,mm^{-1}}$) at miconia site I_1 was 54 per cent higher.

The relationship between throughfall KE_N and intensity was more scattered than that for open rainfall (Figure 4). Previous studies showed throughfall KE_N, particularly that associated with leafdrip, was independent of rainfall intensity (Brandt, 1990), whereas KE_N of open rainfall increased with rainfall intensity (Kinnell, 1980: van Dijk *et al.*, 2002). Calculated KE_N was therefore assumed to be constant (28·1, 19·8, and $16{\cdot}5\,\mathrm{J\,m^{-2}\,mm^{-1}}$) at sites I_1, N_3, and N_4, respectively (Table III). Site I_1 had higher KE_N than open rainfall because $e_{\max} = 23{\cdot}7\,\mathrm{J\,m^{-2}\,mm^{-1}}$. KE_N at the site N_3 was higher than that of open rainfall until rainfall intensity exceeded $23\,\mathrm{mm\,h^{-1}}$ (Equation 7). Similarly, KE_N at the site N_4 was higher than that of open rainfall for intensity values $<13\,\mathrm{mm\,h^{-1}}$ (Equation 7).

Difference in throughfall KE_N among sites was related in part to different distributions of drop size and fall velocities associated with various canopies (Figures 5 and 6). Throughfall drops were greater than those of open rainfall at each site (Figure 5). D_{50} was largest at the N_4 site, but D_{90} was largest at the I_1 site (Table III). The fractions of drops exceeding 3 mm in diameter were 62, 37, and 81 per cent at the sites I_1, N_3, and N_4, respectively, and 8, 5, and 5 per cent for drop fractions exceeding 6 mm in diameter. Throughfall at site N_3 had the most equal proportions of large and small drops. With respect to fall velocity, miconia site I_1 had higher velocity than the others because site I_1 had greater tree height and branch height (Figure 6). The estimated average falling heights from the velocity were 5–8 m at site I_1, 4–5 m at site N_3, and 2–3 m at the site N_4 (cf. Nanko *et al.*, 2008b), values that correspond to canopy structure (Table II). All velocities were less than terminal velocity. Drops with diameters exceeding 3 mm must fall at least 12 m to accelerate to terminal velocity in air at 1 hPa and 20°C (Wang and Pruppacher, 1977).

DISCUSSION

The effects of ground cover on soil erosion are well established. Splash detachment, runoff production, and soil erosion generally increase as the proportion of ground cover decreases (Osborn, 1954; Elwell and Stocking, 1976; Gilley *et al.*, 1986; Woo and Luk, 1990; Loch, 2000; Smets *et al.*, 2008). Raindrop impact on soil surface plays two roles for inter-rill erosion: soil splash and seal formation. Continuous and concentrative raindrop impacts over a short period cause soil splash detachment on the forest floor (Nanko *et al.*, 2008a). Infiltration capacity also decreases with increasing kinetic energy of drops (e.g., Agassi *et al.*, 1985; Shainberg *et al.*, 2003; Nanko *et al.*, 2010). Surface runoff and erosion are often severe if ground cover declines below 50 per cent

(Elwell and Stocking, 1976). In contrast with native forest sites in Hawai‘i, areas under miconia typically have much less ground cover. For example, the sites shown in Figures 2 and 3D have estimated cover values near the 50 per cent threshold. Erosional evidence at these sites included rills and soil pedestals. Although we did not quantify ground cover systematically at the sites, visual estimates allow us to conclude that the cover that typically occurred was not sufficient to form a protective layer capable of mitigating erosion processes.

The energy associated with large drops falling from vegetation canopies is also critical in assessing erosion potential. For open rainfall, the fraction of kinetic energy associated with drops >2 mm (KE_{0a}) ranged from 15 to 42 per cent, with the value increasing with rainfall intensity (Table III; Figure 7). However, large drops (>3·8 mm) were not observed; thus, KE_{0b} was zero for all rainfall events. In contrast, the fraction of KE_{0a} and KE_{0b} for throughfall was much higher: >73 and 31 per cent at all sites. The fractions of KE_{0a} were similar between miconia site I_1 and site N_4; however, the fraction of KE_{0b} was much higher in the miconia stand (60 vs 41 per cent), indicating the potential for greater surface erosion in the former.

To demonstrate how the erosivity varied among canopy species under a same rainfall condition, the total kinetic energy and effective kinetic energy were estimated at the three sites for the observed rainfall at the site N_4 using the observed throughfall characteristics (Figure 8). Total kinetic energy was higher in open rainfall than each throughfall site; however, the effective kinetic energy was higher for throughfall. Kinetic energy components differed among the three canopy species. Importantly, the effective kinetic energy was largest at the miconia site. This higher value combined with a high KE_{0b} supports the notion that miconia invasion could increase the erosivity of a site by affecting throughfall drop properties. In such an instance, the decreasing canopy thickness associated with transition to miconia could increase all the following: initial throughfall depth, proportional volume and number of large throughfall drops, and throughfall kinetic energy (Nanko *et al*., 2008b).

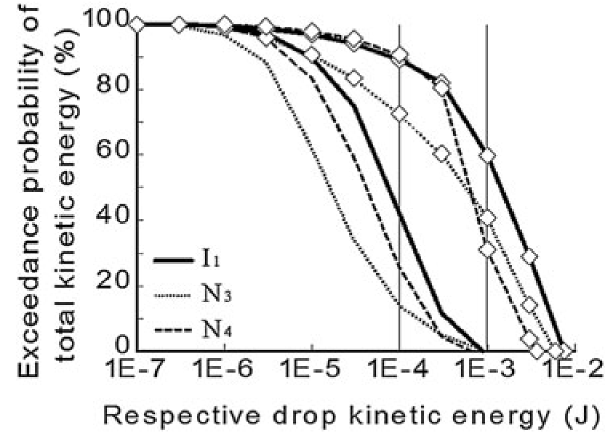

Figure 7. Exceedance probability of drop kinetic energy determined at observation sites I_1, N_3, and N_4 (Table II). Lines with symbols refer to throughfall; those without symbols, rainfall.

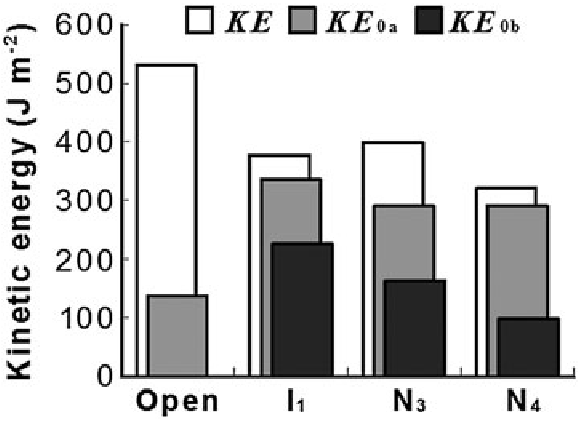

Figure 8. Comparison of kinetic energy among open rainfall and three throughfall sites (I_1, N_3, and N_4) observed or estimated at each site for the rainfall event at N_4 during 21–22 Dec 2007. Observed data are used for open rainfall and for the N_4 site. Estimated values are used for sites I_1 and N_3.

The situation of miconia is somewhat analogous to that of unmanaged cypress plantations in Japan (Miura *et al*., 2002; Onda *et al*., 2010; Wakiyama *et al*., 2010). Monotypic stands typically have little protective ground cover vegetation to mitigate the impact of throughfall dripping from uniform canopies. Miconia invasion is, however, more serious because throughfall drop size is larger. For example, D_{50} is less than 2·5 mm under Japanese cypress (Nanko *et al*., 2008a, 2008b), compared with 3·8 mm under miconia. Moreover, the annual precipitation at the study sites in Hawai‘i (ca. 3800 mm) is twice that at the study sites in Japan (ca. 1700 mm). Although monitored rainfall events were limited, this study provides useful insight for understanding the erosive potential by miconia invasion.

CONCLUSIONS

Measurements from the Island of Hawai‘i suggest several factors potentially accelerate soil erosion in invading miconia stands. Low light levels below miconia canopies inhibit the growth of understory vegetation that provides protection from throughfall drop impact. Rapid rates of decomposition of organic litter on the forest floor also limit surface cover development. Compared with native **‘ōhi‘a** stands, throughfall energy is greater in miconia stands because a higher proportion of large drops exceeds erosive thresholds. This difference is, in part, related to miconia having a single, uniform canopy instead of a multi-story canopy that is often associated with native **‘ōhi‘a** forest stands. Thus, exposed roots found in stands invaded by miconia are likely the direct result of high-energy throughfall striking a ground surface lacking sufficient protective surface cover to mitigate erosion processes. Invasive miconia not only represents an ecological threat to sensitive ecosystems but may also act as an agent of land degradation by accelerating surface erosion.

ACKNOWLEDGEMENTS

The authors are grateful to Kim Burnett, Donna Lee, and Ryan Smith for their help in designing the study and finding suitable study sites. We thank the Hawai'i Tropical Botanical Garden (HTBG), and especially Sean Callahan, Horticulturist and Garden Manager, for guiding us to miconia-infested sites and allowing us to conduct measurements on HTBG land. Jan Schipper and Jean Franklin of the Big Island Invasive Species Committee kindly provided a map of the miconia distribution on Hawai'i Island. This research was supported by Hawai'i Department of Land and Natural Resources/Hawai'i Invasive Species Council Award "Ecological, Hydrological, and Economic Impacts of miconia in Hawai'i", US Fish and Wildlife Service Agreement number 122004J001, and by the Pacific Island Ecosystems Research Center (PIERC), USGS. Lastly, we acknowledge Lloyd Loope of PIERC whose leadership and dedication to understanding and mitigating species invasion in Hawai'i have been a great service to the ecosystems and people of Hawai'i.

REFERENCES

Agassi M, Shainberg I, Morin J. 1985. Infiltration and runoff in wheat fields in the semi-arid region of Israel. *Geoderma* **36**: 263–276.

Allison SD, Vitousek PM. 2004. Rapid nutrient cycling in leaf litter from invasive plants in Hawai'i. *Oecologia* **141**: 612–619. DOI: 10.1007/s00442-004-1679-z

Atlas D, Srivastava RC, Sekon RS. 1973. Doppler radar characteristics of precipitation at vertical incidence. *Reviews of Geophysics and Space Physics* **11**: 1–35.

Austin AT, Vitousek PM. 2000. Precipitation, decomposition and litter decomposability of *Metrosideros polymorpha* in native forests on Hawai'i. *Journal of Ecology* **88**: 129–138. DOI: 10.1046/j.1365-2745.2000.00437.x

Blanchard DC. 1953. Raindrop size distributions in Hawaiian rains. *Journal of Meteorology* **10**: 457–473.

Brandt J. 1990. Simulation of the size distribution and erosivity of raindrops and throughfall drops. *Earth Surface Processes and Landforms* **15**: 687–698.

Cordell S, Goldstein G. 1999. Light distribution and photosynthesis of *Metrosideros polymorpha* forests at both ends of a substrate age gradient in Hawai'i. *Selbyana* **20**: 350–356.

Denslow JS. 2003. Weeds in paradise: thoughts on the invisibility of tropical islands. *Annals of the Missouri Botanical Garden* **90**: 119–127.

van Dijk AIJM, Bruijnzeel LA, Rosewell CJ. 2002. Rainfall intensity–kinetic energy relationships: a critical literature appraisal. *Journal of Hydrology* **261**: 1–23. DOI: S0341-8162(02)/S0022-1694(02)00020-3

Elwell HA, Stocking MA. 1976. Vegetal cover to estimate soil erosion hazard in Rhodesia. *Geoderma* **15**: 61–70. DOI: S0341-8162(02)/0016-7061(76)90071-9

Fosberg FR. 1992. Vegetation of the Society Islands. *Pacific Science* **46**: 232–250.

Giambelluca TW, Sutherland RA, Nanko K, Mudd R, Ziegler A. 2010. Effects of *Miconia* on hydrology: a first approximation. In Loope LL, Meyer J-Y, Hardesty BD, Smith CW (eds), *Proceedings of the International Miconia Conference*, Keanae, Maui, Hawai'i, May 4–7, 2009, Maui Invasive Species Committee and Pacific Cooperative Studies Unit. University of Hawai'i at Mānoa. http://www.hear.org/conferences/miconia2009/proceedings/

Gilley JE, Finkner SC, Spomer RG, Mielke LN. 1986. Runoff and erosion as affected by corn residue: Part I. Total losses. *Transactions of the ASAE* **29**: 157–160.

Goarant AC, Meyer J-Y. 2010. Attempting the eradication of *Miconia calvescens* in a comprehensive strategy to control invasive species in New Caledonia. In Loope LL, Meyer J-Y, Hardesty BD, Smith CW (eds.), *Proceedings of the International Miconia Conference*, Keanae, Maui, Hawai'i, May 4–7, 2009, Maui Invasive Species Committee and Pacific Cooperative Studies Unit. University of Hawai'i at Mānoa. http://www.hear.org/conferences/miconia2009/proceedings/

Hall RL, Calder IR. 1993. Drop size modification by forest canopies—measurements using a disdrometer. *Journal of Geophysical Research* **90**: 465–470. DOI: 10.1029/93JD01498

Kinnell PIA. 1980. Rainfall intensity–kinetic energy relationships for soil loss prediction. *Soil Science Society of America Proceedings* **45**: 153–155.

Kinnell PIA. 2005. Raindrop-impact-induced erosion processes and prediction: a review. *Hydrological Processes* **19**: 2815–2844. DOI: 10.1002/hyp.5788

Loch RJ. 2000. Effects of vegetation cover on runoff and erosion under simulated rain and overland flow on a rehabilitated site on the Meandu Mine, Tarong, Queensland. *Australian Journal of Soil Research* **38**: 299–312.

Loh RKH. 2004. Early plant establishment following experimental removal of invasive *Morella faya* (Ait.) Wilbur stands in a Hawaiian forest. PhD dissertation, University of Hawai'i at Mānoa. Honolulu, Hawai'i.

Loope L. 2009. *Miconia calvescens*: a case example of the need for prevention and early detection in the Hawaiian Islands. Page 36 in C. Kueffer and L. Loope (eds.), *Prevention, early detection and containment of invasive, non-native plants in the Hawaiian islands: current efforts and needs*. Pacific Cooperative Studies Unit Technical Report 166. University of Hawai`i at Manoa, Department of Botany, Honolulu, HA.

Loope LL. 2011. Hawaiian Islands: invasions. *In Encyclopedia of invasive introduced species*, Simberloff D, Rejmánek M *(eds)*. University of California Press: Berkeley, CA, 309–319.

Marshall J, Palmer W. 1948. The distribution of raindrops with size. *Journal of Meteorology* **5**: 65–166.

Medeiros AC, Loope LL, Conant P, McElvaney S. 1997. Status, ecology, and management of the invasive plant, *Miconia calvescens* DC (Melastomataceae) in the Hawaiian Islands. *Records of the Hawai'i Biological Survey for 1996*, Bishop Museum Occasional Papers 48: 23–36.

Meyer J-Y. 1994. Mecanismes d'invasion de *Miconia calvescens* en Polynesie Française. *Ph.D. thesis, l'Universite de Montpellier II Sciences et Techniques du Languedoc*. Montpellier, France.

Meyer J-Y. 1996. Status of *Miconia calvescens* (Melastomataceae), a dominant invasive tree in the Society Islands (French Polynesia). *Pacific Science* **50**: 66–76.

Meyer J-Y. 2004. Threat of invasive alien plants to native flora and forest vegetation of eastern Polynesia. *Pacific Science* **58**: 357–375. DOI: 10.1353/psc.2004.0032

Meyer J-Y, Florence J. 1996. Tahiti's native flora endangered by the invasion of *Miconia calvescens* DC. (Melastomataceae). *Journal of Biogeography* **23**: 775–781. DOI: 10.1111/j.1365-2699.1996.tb00038.x

Miura S, Hirai K, Yamada T. 2002. Transport rates of surface materials on steep forested slopes induced by raindrop splash erosion. *Journal of Forest Research* **7**: 201–211.

Morgan RPC. 2005. *Soil erosion and conservation*, third edi. Blackwell Publishing Ltd.: Oxford, 304.

Motooka P, Castro L, Nelson D, Nagai G, Ching L. 2003. Weeds of Hawai'i's pastures and natural areas, an identification and management guide. College of Tropical Agriculture and Human Resources, University of Hawai'i at Mānoa, 184 pp.

Mueller-Dombois D, Fosberg FR. 1998. *Vegetation of the Tropical Pacific Islands*. Springer Verlag: New York.

Murphy HT, Hardesty BD, Fletcher CS, Metcalfe DJ, Westcott DA, Brooks SJ. 2008. Predicting dispersal and recruitment of *Miconia calvescens* (Melastomataceae) in Australian tropical rainforests. *Biological Invasions* **10**: 925–936. DOI: 10.1007/s10530-008-9246-x

Nanko K, Hotta N, Suzuki M. 2006. Evaluating the influence of canopy species and meteorological factors on throughfall drop size distribution. *Journal of Hydrology* **329**: 422–431. DOI: S0341-8162 (02/j.jhydrol.2006.02.036

Nanko K, Mizugaki S, Onda Y. 2008a. Estimation of soil splash detachment rates on the forest floor of an unmanaged Japanese cypress plantation based on field measurements of throughfall drop sizes and velocities. *Catena* **72**: 348–361. DOI: 1S0341-8162(02/j.catena.2007.07.002

Nanko K, Onda Y, Ito A, Moriwaki H. 2008b. Effect of canopy thickness and canopy saturation on the amount and kinetic energy of throughfall: an experimental approach. *Geophysical Research Letters* **35**: L05401. DOI: 10.1029/2007GL033010

Nanko K, Onda Y, Ito A, Ito S, Mizugaki S, Moriwaki H. 2010. Variability of surface runoff generation and infiltration rate under a tree canopy: indoor artificial rainfall experiment using a stand of Japanese cypress

(*Chamaecyparis obtusa*). *Hydrological Processes* **24**: 567–575. DOI: 10.1002/hyp.7551

Onda Y, Gomi T, Mizugaki S, Nonoda T, Sidle RC. 2010. An overview of the field and modeling studies on the effect of forest devastation on flooding and environmental issues. *Hydrological Processes* **24**: 527–534.

Osborn B. 1954. Effectiveness of cover in reducing soil splash by raindrop impact. *Journal of Soil Water Conservation* **9**: 70–76.

Salles C, Poesen J, Govers G. 2000. Statistical and physical analysis of soil detachment by raindrop impact: rain erosivity indices and threshold energy. *Water Resources Research* **36**: 2721–2729.

Shainberg I, Mamedov AI, Levy GJ. 2003. Role of wetting rate and rain energy in seal formation and erosion. *Soil Science* **168**: 54–62.

Sharma PP, Gupta SC, Foster GR. 1995. Raindrop-induced soil detachment and sediment transport from interrill area. *Soil Science Society of America Journal* **59**: 727–734.

Smets T, Poesen J, Bochet E. 2008. Impact of plot length on the effectiveness of different soil-surface covers in reducing runoff and soil loss by water. *Progress in Physical Geography* **32**: 654–677. DOI: 10.1177/0309133308101473

Wakiyama Y, Onda Y, Nanko K, Mizugaki S, Kim Y, Kitahara H, Ono H. 2010. Estimation of temporal variation in splash detachment in two Japanese cypress plantations of contrasting age. *Earth Surface Processes and Landforms* **35**: 993–1005. DOI: 10.1002/esp.1844

Wang PK, Pruppacher HR. 1977. Acceleration to terminal velocity of cloud and raindrops. *Journal of Applied Meteorology* **16**: 275–280.

Whittaker RJ. 1998. *Island biogeography: ecology, evolution and conservation*. Oxford University Press: Oxford.

Woo M-K, Luk S-H. 1990. Vegetation effects on soil and water losses on weathered granitic hillslopes, South China. *Physical Geography* **11**: 1-16.

Zhou G, Wei X, Yan J. 2002. Impacts of eucalyptus (*Eucalyptus exserta*) plantation on sediment yield in Guangdong Province, southern China—a kinetic energy approach. *Catena* **49**: 231–251. DOI: 10.1016/S0341-8162(02)00030-9