A LANDSCAPE ECOLOGY APPROACH TO ASSESSING DEVELOPMENT IMPACTS'IN THE TROPICS: A GEOTHERMAL ENERGY EXAMPLE IN HAWAII

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ABSTRACT

Geographic information systems (GIS) are increasingly being used in environmental impact assessments (EIA) because GIS is useful for analysing spatial impacts of various development scenarios. Spatially representing these impacts provides another tool for landscape ecology in environmental and geographical investigations by facilitating analysis of the effects of landscape pattern on ecological processes and examining change over time. Landscape ecological principles are applied in this study to a hypothetical geothermal development project on the Island of Hawaii. Some common landscape pattern metrics were used to analyse dispersed versus condensed development scenarios and their effect on landscape pattern. Indices of fragmentation and patch shape did not appreciably change with additional development. The amount of forest to open edge, however, greatly increased with the dispersed development scenario. In addition, landscape metrics showed that a human disturbance had a greater simplifying effect on patch shape and also increased fragmentation than a natural disturbance. The use of these landscape pattern metrics can advance the methodology of applying GIS to EIA.

Keywords: landscape ecology, tropical impact assessment, geothermal energy, geographic information systems (GIS), Hawaii

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INTRODUCTION

We examine the use of geographic information systems (GIS) in a hypothetical environmental impact assessment (EIA) scenario that incorporates the tools of landscape ecology. Landscape ecology emphasises the effect of spatial patterns of ecosystems on ecological processes (Turner, 1989). GIS has become an integral tool for both ecologists and environmental impact assessors. First, we discuss the importance of GIS and remote sensing to assess environmental impacts in the

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'Research performed while all authors worked at the U.S. Department of Energy's Oak Ridge National Laboratory, Environmental Sciences Division, Oak Ridge, Tennessee tropics. We also review the use of GIS in ecology and EIA. Then, we suggest how GIS and the principles of landscape ecology can be incorporated in an alternatives assessment in an EIA. Here, we create a hypothetical development and use the tools of GIS and landscape ecology for two purposes: (1) to compare the landscape impacts of two development scenarios and (2) to compare the landscape impacts of a human disturbance (resource extraction) versus a natural disturbance (lava flow). By comparing landscape metrics betwen scenarios, we assessed the relative impact of the disturbances on landscape pattern. We hypothesised that landscape pattern, as represented by the chosen metrics, would differ between the two development scenarios and the natural/human disturbance scenario.

Energy development in the tropics

Energy development will be a critical issue for tropical countries in the future. While the affluent north has made strides in battling environmental degradation, the developing nations in the south (the tropics) are plagued by growing air and water pollution, soil erosion and lack of safe drinking water (El-Ashry, 1991). Companies are expanding operations into some of the world's relatively undisturbed tropical ecosystems. In fact, the next frontier for oil and gas development will be in the humid tropics, where 80 per cent of exploration and production is expected to take place in this decade (Rosenfeld et *al., 1997).* Some of these areas are remote and located near important or sensitive ecosystems. Thus, there is a need for environmental considerations to be brought into the mainstream of economic decision-making. In energy resource developments, it is important to minimise land clearing in sensitive areas (Rosenfeld et *al.,* 1997). Roads can attract hunters, colonists, or invasive and introduced species. Specifically regarding geothermal development, there is growing awareness of this potential resource in the tropics. Among the top ten producers of geothermal electric capacity are the Philippines, Mexico, New Zealand, Indonesia, El Salvador and Nicaragua (Fridliefsson & Freeston, 1994). Other areas where geothermal resources are being assessed and used include Kenya, Guadeloupe (French), the Portuguese Azores, Thailand, Colombia, Guatemala, Taiwan, Vietnam and Zambia (Fridliefsson & Freeston 1994; Quy *et al.,* 2000). Indeed, the Philippines is poised to overtake the US as the largest producer, due to large demand from increasing industrialisation and urban growth in Mindanao (Sussman et *al.,* 1993; Anonymous, 1995; Javellana, 1995). The use of geospatial technologies (remote sensing and GIS) will be important to understand land resource changes as a result of energy and other types of development (see for example, Larnbin, 1997, across the tropics; Pedlowski et *al.,*1997, *in the* Amazon; Mertens ef *al.,* 2000, in Cameroon; Tappan et *al., 2000,* in Senegal).

GIS, ecology and EIA

Developments in GIS over the past decades have sparked keen interest in the field of geography. Ecologists, however, have been slower to see the potential of GIS because early systems were hardware-specific, lacked adequate documentation and were hard to learn and operate (Johnson, 1990). With increased user-friendliness and sophistication, however, GIS has come to be recognised as a keystone technological advance that has catalysed ecology (Johnston, 1998). In her review of ecological applications of GIS, Johnson (1990) notes that GIS has been most frequently used in ecology and natural resources management for: (1) derivation of area or length measurements; (2) spatial intersection functions such as file merging, analysis of spatial coincidence and detection of temporal change; (3) proximity analyses; and (4) derivation of data for input in simulation, growth models or calculation of specific metrics.

GIS is also increasingly used in the environmental consulting industry, and for regulatory purposes, land-use planning and

EIA (Atkinson et *al.,* 1995). Three key reasons why GIS is improving environmental assessment effectiveness are: (1) better analysis; (2) efficient storage and access to digital data; and (3) good visual display capabilities (Joao & Fonseca, 1996). Eedy (1995) reviews the use of GIS in environmental assessment and finds GIS well suited to the management, analysis and display of large, multidisciplinary data sets that are used in EIAs, as well as for post-EIA monitoring and EIA audits. GIS-based industrial environmental management information systems will aid environmental management through all phases: planning, approval, operation, emergency response, decommissioning and regulation (Case & Smith, 1996). The use of GIS could then streamline and standardise the process and increase the number of EIAs being prepared. GIS can also be used for scoping in an EIA framework (Haklay et *al.,* 1998). Common applications of GIS in EIA include route and corridor assessment (e.g. Sankoh et *al.,* 1993;Treweek & Veitch, 1996) andanalysis of landuse change impacts on wetlands and water quality (McCreary *et al.,* 1992).

Joao and Fonseca (1996) acknowledge that the ability of GIS to store, integrate, analyse and display spatial attributes of environmental and socioeconomic data has led to a wider adoption in EIA. They also show that GIS is being used as more than just an expensive graphics machine for: (1) description of the project; (2) impact identification; (3) prediction of impact magnitude; (4) assessment of impact significance such as showing spatial distribution of impact and how it changes with different scenarios; (5) impact mitigation and control; (6) public consultation and participation; and (7) monitoring and auditing. Table 1 lists what EIA practitioners consider

TABLE 1. BENEFITS OF THE USE OF GEOGRAPHIC INFORMATION SYSTEMS (GIS) IN ENVIRONMENTAL IMPACT ASSESSMENT (EIA)

USEFULNESS OF GIS IN EIA	BENEFITS OF GIS FOUND BY EIA PRACTITIONERS	BENEFITS OF GIS IN THE ENVIRONMENTAL REGULATORY PROCESS
1. Management of large data sets	1. Ability to perform spatial analysis and modelling	1. Establishing improved communications and understanding between the proponent team members, regulatory agencies and members of the public
2. Data overlay and analysis of development and natural resource patterns	2. Clearer presentation of results	2. Produces a more complete EIA (more complete identification of impacts)
3. Trends analysis	3. Power for storage, management and organization of spatial data	3. Cost containment (quicker measurement of areas and updating of maps) (Case & Smith 1996)
4. Data sets for mathematical impact models	4. Ability to integrate and manipulate different kinds of spatial information previously unrelated (Joao & Fonseca, 1996)	
5. Habitat analysis		
6. Aesthetic analysis and viewshed analysis		
7. Public consultation		
8. Scoping (Eedy 1995; Haklay *et al.* 1598)		

to be the benefits of GIS. The key problems mentioned by several authors cited in the list are the time/cost for data collection and data conversion to digital form.

In addition to standard EIAs, GIS has been found useful in cumulative effects assessment (CEA), which is the process of systematically analysing and evaluating cumulative environmental change. CEA considers the combined effects of two or more developments (related or independent) and the possible indirect or secondary effects (Cocklin et al., 1992). Smit and Spaling (1995) list six approaches to CEA: spatial analysis, network analysis, biogeographic analysis, interactive matrices, ecological modelling and expert opinion. GIS was judged a useful tool for the spatial analysis method because "changes in spatial distribution of environmental attributes are captured by documenting distributions at specific time intervals and these are correlated with changes in land use/development pattern" (Smit & Spaling, 1995).

GIS, landscape ecology and alternatives assessment

A common use of GIS is for monitoring land-use change. Coupled with the increased presence of GIS since the 1980's has been the renewed stature of landscape ecology and, oftentimes, both are closely linked (Haines-Young et al., 1993). Landscape ecology is concerned with broader geographic scales and change over time, and seeks to associate ecological processes with landscape pattern (Urban et al., 1987; Turner, 1989; Forman, 1995a; Forman, 1995b). Smit and Spaling's (1995) "biogeographic analysis" method of CEA is essentially a landscape ecology approach. Landscape metrics are values or indices used in landscape ecology that are calculated on GIS data and which quantify landscape pattern (O'Neill et al., 1988; Baker & Cai, 1992; Li & Reynolds, 1993; Forman, 1995a; Riitters et al., 1995; Diaz, 1996; Gustafson, 1998). Integrating GIS data with programmes to calculate landscape metrics is a method used to monitor land-use change in local areas (Ahern et *al.*, 1992; LaGro & DeGloria, 1992; Haines-Young et *al.*, 1993; Moss & Davis, 1994), states and regions (Turner, 1990a; Hunsaker *et* al., 1994; O'Neill *et* al., 1996). Research in landscape ecology has accelerated in part due to GIS; new spatial tools have given ecologists an unprecedented capacity to measure and understand spatial heterogeneity (Turner & Carpenter, 1998). Spatial heterogeneity refers to the complexity and variability of a system property in space (such as land cover or vegetation types, plant biomass and soil nutrients).

Prior to GIS, the ability to explore the effect of different project configurations and produce maps of the results was often cost-prohibitive (Case & Smith, 1996). GIS has streamlined alternative development/management plans analysis. The combined use of GIS and landscape ecology to study the effect of landscape pattern has been particularly evident in analysing forestry practice impacts (Baskent & Jordan 1995; Diaz, 1996; Tinker et *al.*, 1998). The analysis of landscape patterns resulting from forestry activities has been performed on both simulated landscapes (Franklin & Forman, 1987; Li et *al.*, 1992) and real ones (Ripple *et al.*, 1991; Liu *et al.*, 1993; Spies et al., 1994; Gustafson & Crow, 1996). GIS and landscape ecology have also been used to compare impacts from alternative management plans or siting locations (Hanson *et al.*, 1993; Atkinson *et al.*, 1995; de Gouvenain, 1995; Gustafson & Crow, 1996).

A hypothetical development plan on Hawaii

The purpose of this study is to combine GIS with the tools of landscape ecology in an EIA scenario. Our objectives are to use the tools of GIS and landscape ecology to: (1) compare the landscape impact of a condensed versus a dispersed development scenario and (2) examine how landscape pattern impacts differ when comparing natural and human disturbances. Hawaii provides the opportunity to meet these objectives, Besides urbanisation and tourism-related development, there is also

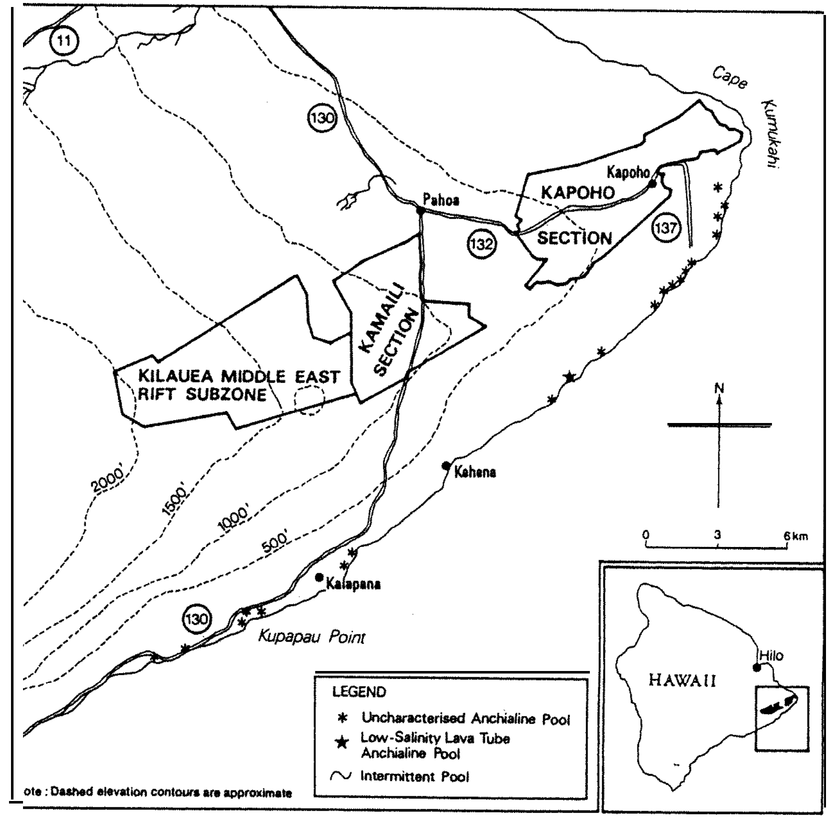

*Figure I. **Geothermal resource subzones (GRS) on the eastern tip of Hawaii where energy development can take place, also showing general topography (elevation is in feet) and anchialine pools (brackish ponds often containing rare or endangered species).***

potential development related to resource extraction activities such as geothermal energy development as Hawaii attempts to become more energy self-sufficient (Shupe, 1982; Shupe, 1984; Hannah, 1990; Harris, 1990); the associated active volcanism also results in the natural disturbances of lava flows (Staub & Reed, 1995).

Our hypothetical development involves geothermal development along areas on the eastern side of Hawaii (Figure 1). For about two decades, plans have been put in place to exploit Hawaii's geothermal resource and even transport excess energy via underwater cable to Oahu in order to satisfy growing energy demands from Honolulu and the tourism industry (Edelstein & Kleese, 1995). Methods used here, however, could also apply to other types of development as well, including logging and residential/commercial projects. Figure 1 shows the state-designated geo-thermal resource subzones (GRS) bounding the region where geothermal energy development can potentially occur (Hannah, 1990). The Kilauea Middle East Rift Subzone is 3,740 ha, and the Kamaili and Kapoho sections encompass roughly 2,242 ha and

035 ha, respectively. Development for :othermal energy production might include 'eas housing the geothermal plants and ıildings, areas of satellite wells, failed :ploratory wells and access roads to connect ıese elements. Landscape patterns were ıantified to compare the landscape impact f different development scenarios:

the natural vegetation of the area, based on a digital GIS layer;

the natural vegetation of the area with existing roads overlaid onto it;

a "disperses' development scenario, which included wells, smaller central power plant units and greater length of roads, and

a "condensed" case, which included larger central power plant units but fewer power plant units in total, thus reducing the length of new access roads needed.

The second part of this study investigates ıe effect of a human disturbance (resource xtraction development) versus a natural isturbance (lava flows). Existing lava flows ʋithin the GRSs and their effect on landscape attem was studied with commonly used ındscape metrics.

ɅETHODS

'he following scenarios for a geothermal evelopment derive from consultations with :eologists and geothermal consultants and ɾrevious smaller geothermal developments on Iawaii (e.g. Edelstein & Kleese, 1995). Tiffer t al. (1993) also describe the general nature ıf geothermal developments. Initially, xploratory wells would be needed for ;eothermal energy production; these would ıe 0.4 ha and would include areas for the drill ig, a holding pond for water to quench ɔotential well blowouts and a service yard ʋhere equipment and other materials would ɔe stored. In addition, access roads are needed :o connect these sites. For sites where there is success in finding appropriate geothermal resources, the project would require three types of wells: production, injection and monitoring. Areas cleared for development in the two energy development scenarios could produce 720 megawatts (MW), with approximately 576 MW net capacity available for transmission out of the GRSs. Each unit would consist of a central power plant site with the power plant and production/ reinjection wells. Satellite well pads and associated well types would be linked with each central unit as well.

The procedure to design two development scenarios was implemented using ARC/INFO GIS software on a UNIX workstation platform. Basically, development scenarios were overlaid onto the vegetation/land cover GIS layer. Similar techniques were used to study fragmentation in Wyoming (Tinker et al., 1998). Generating locations for geothermal well sites was done by overlaying a grid with numbered cells onto the GRSs. A random number programme allowed selection of sites for exploratory wells; a certain fraction of these were considered successful and developed into the central power plant sites. For successful sites, a second step located satellite well pads at a random direction and distance within a threshold. ARC/INFO commands were used to select centroids of the grid cells and to create buffers around the centroids, creating circular areas that would represent the cleared, disturbed areas for development. Two development scenarios were designed. One was a dispersed case having more central power plants with a lower production capacity, and the second was a condensed case requiring fewer central power plants and satellite sites but having greater power capacity. Constraints for well site selection and placement were derived from data layers in the GIS (Table 2). Existing vegetation was derived from maps based on aerial photograph interpretation (Lamoureaux et al., 1985). These were digitised and rasterised at a 10-m grid cell size. Vegetation types occurring in the study area are shown in Figures 2 and 3. Trettin et al. (1995) detail the vegetation types. These include lava, scrub, agriculture, mixed mesic forest, and variations of the dominant native ohia (*Metrosideros polymorpha*) forest such as ohia-uhulu woodland, ohia-fern forest, ohia/fern exotic subcanopy forest, ohia kukui forest and ohia/exotic subcanopy forest.

TABLE 2. CONSTRAINTS IN PLACING GEOTHERMAL RESOURCE FACILITIES

FEATURE	DISTANCE (m)	DATA SOURCE
Threatenedkndangered species	75-2,400	The Nature Conservancy Heritage GIS
Existing dry wells	500	Digitised from existing maps
Existing active/potentially active well sites	500	Digitised from existing maps
Existing lava flow and active areas	500	US Geological Survey
Residences	400	Digitised from colour infra-red aerial photographs
Culturally significant sites	152	Digitised from existing report figures
Ohia/fern forest with native species	50	Digital vegetation data

For the dispersed case, a total of 138 sites were designated for clearing (Figure 4). There were 24 central powerplant sites (each 9.3 ha), 48 satellite power plants (each 2.6 ha) and 66 failed exploratory well sites (each 0.4 ha). The final placement of some sites was slightly adjusted due to overlap with other sites and slight overlap with constraint areas. Roads were also created to connect sites to each other and to existing roads. For the dispersed case, 12 central power plant units were placed in the Kapoho subzone (the most human-impacted zone), and six each in the Kamaili and Kilauea zones.

A condensed site plan was also created (Figure 5). This development scenario could be put into practice due to the presence of a 1955 fissure zone, where the probability for greater geothermal resource would be higher. In this scenario, central and satellite areas were enlarged, which resulted in fewer cleared development sites and a shorter length of new access roads. For this high production development scenario, each central power plant was 22.7 ha, with each satellite site being 2.8 ha. There were 18 failed exploratory wells of 0.4 ha and six central power plant units, each having three satellite well sites. An additional criterion for this condensed case development scenario was that it be located within 460 m of a 1955 fissure zone (to ensure higher production capacity). Two central power plant units were placed in the Kapoho subzone, three in the Kamaili subzone and one in the Kilauea Middle East Rift Subzone. As with the dispersed case development scenario, roads were added to connect all sites (including failed wells). These roads were then buffered at 10 m. Existing roads were obtained from US Geological Survey Digital Line Graphs.

Landscape metrics

Vegetation communities in the GRSs comprise a mosaic that reflects natural succession and the effects of past disturbances. The arrangement and composition of these communities influence landscape functions (e.g. forest bird habitat, biotic diversity). Accordingly, analyses of the pattern and arrangement of these communities on the landscape may provide a useful basis for

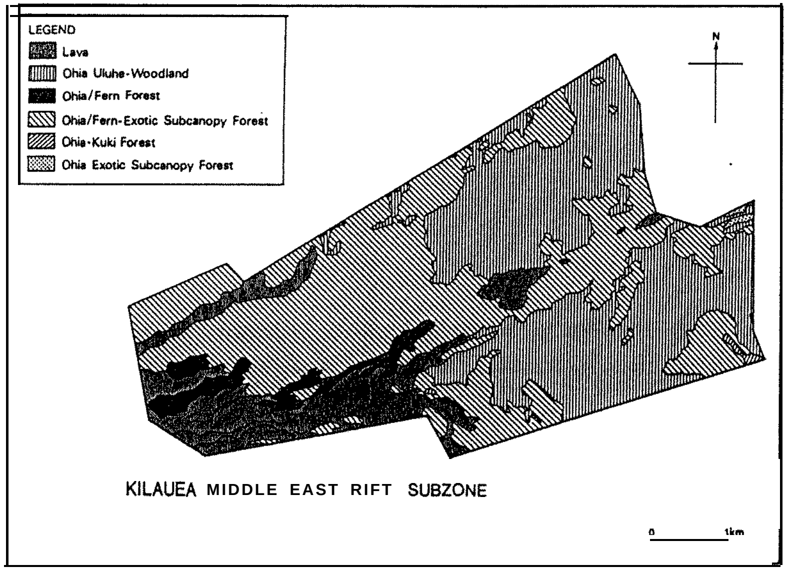

Figure 2. Vegetation and lava occurring within the Kilauea Middle East Rift Subzone (based on Lamoureaux et al. 1985). The vegetation and landscape in this area is more pristine than in the other subzones.

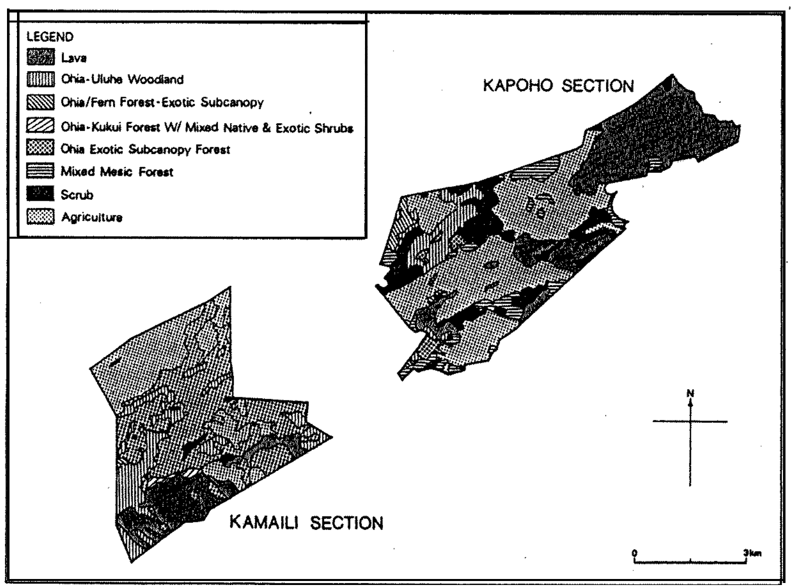

Figure 3. Vegetation and lava occurring in the Kamaili and Kapoho sections (based on Lamoureaux et al. 1985). Greater agricultural and urban development occurs in these areas.

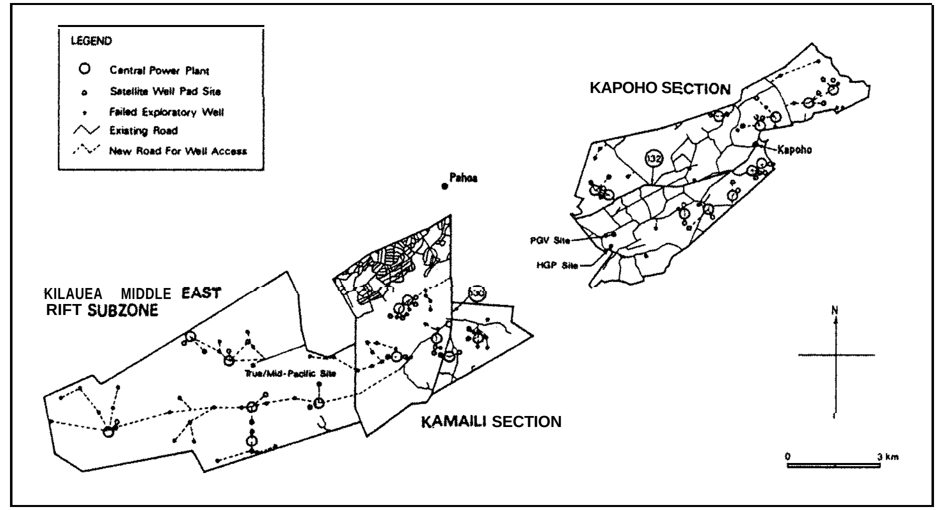

Figure 4. A dispersed development case of geothermal development within the GRSs. Also shows some initial geothermalplants, including the True/Mid-Pacific, PGV (Pacific Geothermal) and HGP (Hawaii Geothermal Project) sites.

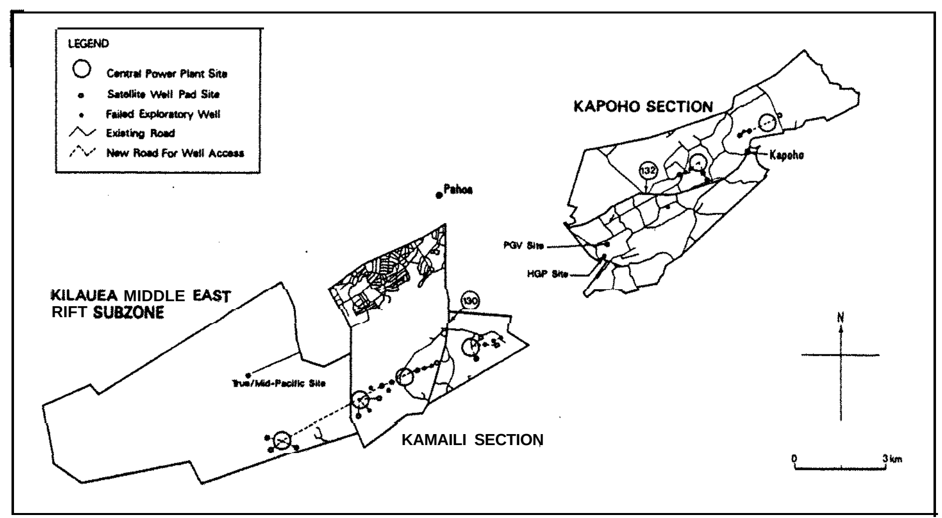

Figure 5. A condensed development case of geothermal development within the GRSs. Also shows some initial geothermal plants, including the True/Mid-Pacific, PGV and HGP sites.

that with existing roads, road to ohia forest edge (all ohia forest types) comprised 7.1 per cent of total edge. That percentage more than doubles after the dispersed development case, while it increases much less after the condensed case.

Table 4 presents average and maximum patch size of the vegetation types. With current roads (existing conditions), patch size significantly decreases, especially in the ohia-uluhe woodland. The dispersed case further reduces average patch size significantly for several ohia forest types, while the reduction is not as severe in the condensed case. Existing conditions greatly reduce the largest patch within the subzones and the reduction is greater with the dispersed case. The maximum patch size for the ohia-uluhe woodland and the ohia/exotic subcanopy forest are greatly reduced. The condensed case values, however, are fairly similar to the existing conditions. Generally, the dispersed development case creates the most patches and the smallest patches. The actual size of the largest patch is also smallest for the dispersed case. Patch size effects are important in determining impacts on species with specific habitat size requirements.

The changes in landscape pattern found here are similar to those found in other locales. Tinker et *al.* (1998) found that clearcuts and roads simplified patch shape in the Rocky Mountains. In our study area, the effect of the existing roads reveals patch simplification as expressed by decreased spatial complexity. Because there are so many existing roads, the effect of our developments are slight on contagion and spatial complexity, but are revealed more strongly in edge amounts. Condensing the development lessens the negative effects, with the condensed case having landscape metric values closer to the original landscape. Tinker *et* al. (1998) document similar findings with clearcutting in the Rockies, noting that aggregating clearcuts into larger units may reduce fragmentation effects when compared to dispersing smaller units of clearcuts. Increased spatial complexity generally indicates human disturbance in a relatively natural landscape. However, if a landscape has initially high human impact, there could be some sources of confusion, such as landscaping activities creating a patch of planted trees or artificial ponds with straight boundaries.

Comparing the ecological effects of condensed versus dispersed development is important in Hawaii to assess problems posed by exotic species. Guava trees can penetrate into native ohia forest from cleared areas. The loss of the native ohia canopy can result in greater numbers of introduced birds at the expense of native birds (Hodges et al., 1986). The direct removal by humans of the ohia canopy is compounded by the natural ohia dieback over recent decades, often resulting in large openings in the canopy for considerable time periods; the potential impact of this dieback on ecosystem processes is substantial (Akashi & Mueller-Dombois, 1995). An insect-induced dieback of *Myrica faya* (faya or fire tree) is suspected to increase opportunities for introduced grasses (Adler *et al.*, 1998), which might spread more easily from disturbed areas. Basically, fragmentation affects species. The effects of fragmentation include conversion of interior forest to edge, reduction in genetic diversity (Aldrich & Hamrick, 1998) and increasing yearly variability in area-sensitive bird species, thereby reducing community stability (Boulinier et al., 1998). Other effects are reduction in quantity and quality of late-successional habitat, and changes in microclimate and nest predation (Saunders et *al.*, 1991; Tinker *et al.*, 1998).

Symptoms of the "fragmentation syndrome" – increases in edge density and fundamental changes in the size and shape of landscape patches – described by Tinker et *al.* (1998) occur in our study. The development had similar effects to clearcutting, resulting in patches with less convoluted edges. The effect on contagion and spatial complexity

TABLE 4. AVERAGE AND MAXIMUM PATCH SIZES RESULTING FROM DEVELOPMENT SCENARIOS

VEGETATION ONLY	AVERAGE PATCH SIZE (ha)				MAXIMUM PATCH SIZE (ha)			
	Vegetation only	Existing condition	After dispersed case	After condensed case	Vegetation only	Existing conditions	After dispersed case	After condensed case
Lava	82.3	28.2	19.5	25.0	657.4	436.9	401.0	434.4
Ohia/uluhe	49.3	25.6	17.2	23.1	973.6	964.9	441.0	846.5
Ohia/fern	40.6	40.6	17.2	40.6	63.0	63.0	55.0	63.0
Ohia/fern exotic subcanopy	56.0	48.0	25.4	46.6	1,120.1	1,079.5	830.7	1,079.5
Ohia/kukui	17.0	11.3	8.4	5.7	25.7	25.4	14.1	9.3
Ohia/exotic subcanopy	33.8	11.0	9.0	10.3	703.3	402.8	207.4	399.6
Mixed mesic forest	8.2	4.5	3.8	4.5	52.2	52.2	41.1	52.2
Scrub	13.7	4.9	4.9	3.3	110.9	103.3	103.3	103.3
Agriculture	73.6	5.0	5.0	4.8	1,160.5	89.1	89.1	89.1

values was less; in fact, the condensed plan in some cases was similar to the existing land cover. Invasive fauna pose threats as well. Over 40 species of exotic ants are reported in Hawaii (Reimer, 1994; Wetterer, 1998). Recent surveys in the geothermal areas near Mount Kilaueau showed several exotic ants common in areas disturbed by geothermal/human activity. These ants have been implicated in the extermination of endemic insects and can impact other fauna through direct attack on hatchlings or newborn mammals, or through elimination of invertebrate prey for some species, in particular, breeding passerine birds (Wetterer, 1998). While at this time non-native ants are rare in intact forest, *Paratrechina bourbonica* can colonise intact forests.

Natural versus human disturbance

The digitised vegetation maps define lava flow areas and permit comparison of human versus natural landscape changes. We hypothesised that landscape metrics would differ: patches generated by natural disturbances are fundamentally different from patches created by human activities (Tinker *et al.*, 1998). The Kilaueau Middle East Rift Subzone and Kamaili sections were analysed. For the "no lava" scenarios, lava polygons in the GIS were recoded to a vegetation type based on neighbouring vegetation patches, effectively reverting the landscape back to a pre-lava flow condition. The scenarios are: (I) vegetation only (no lava);(2) dispersed case (wells, existing roads, new roads) with no lava; (3) condensed case (wells, existing roads, new roads) with no lava; and (4) vegetation with lava (no existing roads).

Scenarios 1 and 4 describe the landscape pattern impacts of the lava flows (Table 5). Dominance decreases due to a relatively large addition of lava at the expense of the predominant forest cover (creating a more balanced mix of cover types) but contagion and spatial complexity remain very similar in the pre- and post-lava flow conditions. The comparison of scenario 1 with the human impacts of scenarios 2 and 3, however, show that both contagion and spatial complexity decrease substantially. Roads effectively bisect and fragment vegetation communities. Moreover, roads generally add a smooth linear shape on the landscape; their presence serves to decrease the irregular boundaries of vegetation patches in a natural environment. Roads also serve to increase the amount of open edge within forested areas. The highest percentage of road/ohia edge or lava/ohia edge occurs with the dispersed case. This result occurs despite the fact that the area of lava is more than 2.5 times greater than the area of land cleared in the development scenarios (Table 6).

The lava flow is more compact, with higher area-to-perimeter ratios than the cleared area and roads of the development scenarios. Thus, one would expect relatively lower edge and higher contagion values. Furthermore, the edges created by humans differ from natural edges (Tinker *et al.*, 1998). Edges from a lava flow may have a less abrupt transition, with some dead trees in transitional areas. The average patch size (Table 7) is higher for the natural disturbance (lava) except for the ohia/fern and ohia/fern exotic subcanopy forest, because the condensed case places only one central power plant and few new roads in the Kilauea subzone where these vegetation types occur. The same situation applies to maximum patch size as well.

We analysed the potential impact of two invasive organisms (ants and guava) estimating that ants disturb or invade areas up to 100 m from sites disturbed by geothermal activities/roads, and guava up to 50 m . These values are chosen more to demonstrate the effects of different development patterns than as a precise measure of forest penetration capability (see Table 8). The total disturbed area of the development scenarios reveals dramatic effects of dispersing the development, with the area affected in the dispersed case nearly five times that in the condensed case (Table 9). This would likely have ecological consequences and make native intact forest more vulnerable to invasion by these organisms.

TABLE 5. LANDSCAPE METRICS COMPARING ANTHROPOGENIC AND NATURAL DISTURBANCES

SCENARIO	DOMINANCE	CONTAGION	SPATIAL COMPLEXITY	ROAD/OHIA OR LAVA/OHIA EDGE (m)	TOTAL EDGE (m)	PERCENTAGE ROAD/OHIA OR LAVA/OHIA EDGE TO TOTAL EDGE
1. Vegetation only (no lava)	0.230	0.939	1.274	NA	18,672	–
2. Dispersed case, no lava	0.223	0.871	1.099	15,819	46,739	33.8
3. Condensed case, no lava	0.240	0.879	1.087	6,952	38,039	18.3
4. Vegetation with lava, no existing roads	0.209	0.931	1.270	6,859	23,753	28.9

TABLE 6. TOTAL AREA (%) OF LAND CLEARED FOR THE DISPERSED AND CONDENSED DEVELOPMENT SCENARIOS IN THE KILAUEA AND KAMAILI SECTIONS

SCENARIOS (Kilauea & Kamaili)	LAND AREA CLEARED (%)
Dispersed case	5.0
Condensed case	3.4
Lava	13.7

TABLE 7. AVERAGE AND MAXIMUM PATCH SIZES FROM HUMAN AND NATURAL DISTURBANCES

VEGETATION TYPE	AVERAGE PATCH SIZE (ha)				MAXIMUM PATCH SIZE (ha)			
	Vegetation only (no lava)	Dispersed case (no lava)	Condensed case (no lava)	Vegetation with Lava (no existing roads)	Vegetation only (no lava)	Dispersed case (no lava)	Condensed case (no lava)	Vegetation with Lava (no existing roads)
Lava	–	–	–	62.8	–	–	–	402.1
Ohia/uluhe	81.1	30.1	54.6	69.1	1,040	440.9	846.5	973.6
Ohia/fern	335.9	55.7	335.9	40.6	3,35.9	315.0	335.9	63.0
Ohia/fern exotic subcanopy	128.8	53.6	96.5	63.1	1,697.6	1,518.5	1,657.0	1,120.1
Ohia/kukui	17.0	8.4	5.7	17.0	25.7	14.1	9.3	25.7
Ohia-exotic subcanopy	148.7	15.3	16.9	59.6	1,048.2	207.4	400.3	703.3
Mixed mesic forest	–	–	–	–	–	–	–	–
Scrub	5.9	1.8	2.0	5.9	11.4	11.2	11.2	11.4
Agriculture	44.6	2.4	2.4	44.2	361.2	29.9	29.9	361.2

TABLE 8. AREA AFFECTED BY INVASIVE ORGANISMS IN DEVELOPMENT SCENARIOS

Organism	DISPERSED CASE Area affected (km^2)	CONDENSED CASE Area affected (km')
Ant	8.1	1.8
Guava	4.3	0.9

TABLE 9. EXTENT OF LAND CLEARED FORTFIE DISPERSED AND CONDENSED DEVELOPMENT SCENARIOS

SUBZONE	DISPERSED CASE	CONDENSED CASE
Area ofdevelopment (km^2)		
Kilauea	0.97	0.31
Kamaili	0.97	0.96
Kapoho	1.81	0.64
TOTAL	3.75	1.91
Length of new roads (km)		
Kilauea	30.1	4.0
Kamaili	14.1	7.3
Kapoho	17.4	3.0
TOTAL	61.6	14.3

CONCLUSION

While previous studies have shown a GIS framework to be useful in assessing landscape impacts, we advanced that methodology by using landscape pattern metrics to quantify changes in landscape pattern that occur as the result of development (including fragmentation levels), edge amounts and patch shape. Assessing change is important to understand potential impacts on populations of native forest-interior birds and susceptibility to invasion by exotic species. Qualitative assessments are inadequate to evaluate such impacts.

In the development scenarios examined here, the condensed case had less severe impacts, primarily in terms of amount of edge created. Compared to existing conditions, there was a 245 per cent increase in roadlohia edge in the dispersed case versus a 44 per cent increase in the condensed case. The average patch size for the native ohia/uluhe vegetation type decreased 33 per cent in the dispersed case versus 10 per cent in the condensed case, while the maximum patch size for the ohia/uluhe vegetation type decreased 54 per cent in the dispersed case versus 12 per cent in the condensed case. These changes can impact organisms having certain area requirements.

Appreciable differences in landscape metric values were observed when comparing natural versus human distur-bances. The natural disturbance (lava flow) was more clumped in shape and did not fragment the landscape as much as the addition of new roads, particularly in the dispersed development scenario. In terms of a potential for exotic invasions caused by new edge, the amount of edge created by this particular natural disturbance was not appreciably different from the condensed development scenario. Indices of contagion and spatial complexity, however, were appreciably different. To assess the true impact of these disturbances, organism-specific studies need to be performed to understand particular responses to landscape pattern.

To some extent, landscape metrics are redundant, for example, contagion and dominance (O'Neill *et al.,* 1996). Some researchers have examined the main aspects of pattern and determined that landscape texture (indicating a fine- versus course-grained landscape), and patch shape and size are important and recurring aspects of landscape pattern (Li & Reynolds, 1995; Riitters et *al.,* 1995; Tinker *et al., 1998; Griffith* et *al.,* 2000). Thus, perhaps a smaller set of metrics could benefit operational use of this methodology – though some consider assembling a parsimonious set may be difficult (McGarigal, 1999). In conclusion, this demonstration of landscape impacts from development shows that a more thorough analysis of environmental impacts can be performed by analysing spatial impacts of land clearing using the tools of GIS and landscape ecology.

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CHARACTERISATION OF OPTICAL WATER QUALITY IN BUNAKEN NATIONAL MARTNE PARK, NORTH SULAWESI, INDONESIA

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ABSTRACT

Effective passive optical remote sensing of submerged coral reef ecosystems requires not only appropriate atmospheric correction, but also water column correction. Algorithms accounting for atmospheric effects are fairly well established and readily available, but water column correction algorithms are still under development. Many approaches to water column correction assume horizontal homogeneity and strict adherence to Beer's Law of logarithmic vertical attenuation, which may not be the case in many coral reef ecosystems. Water column optical properties were measured using a multispectral dropsonde radiometer in Bunaken National Marine Park, North Sulawesi, Indonesia, to examine the vertical and horizontal variability of light in a typical coral reef environment. This largely descriptive case study demonstrates the complexity of the interaction of light in shallow coastal environments with often highly reflective substrata and serves to warn against assumptions of water optical property homogeneity. Downwelling attenuation coefficients are provided for use in water column correction of future remote sensing missions.

Keywords: remote sensing, coral reefs, water optical properties, Indonesia

INTRODUCTION

Extensive and pervasive demands for coastal resources coupled with rapid increases in coastal population are contributing to degradation of the coastal zone such that coral reefs around the world are being damaged and destroyed at a seemingly accelerating rate (Hoegh-Guldberg, 1999). The serious global decline of coral reefs is of urgent concern, for a coral community is but one component of a collection of highly integrated and interrelated biological communities, such as seagrass, mangroves and mudflats. Optical remote sensing, which cannot totally replace. traditional means of coral reef investigation, may augment and improve our baseline inventory while reducing the time and cost requirements of a coastal zone survey (Holden & LeDrew, 1998).

One major limitation of passive optical remote sensing is that water depth and water quality variations are indistinguishable from bottom type variations (Khan *et al*., 1992). Therefore, Philpot (1987) warned against the temptation to interpret readily observable variations in remotely sensed water colour and brightness as a direct indicator of water depth, water quality or bottom type. Instead of direct visual interpretation, appropriate water column' correction must be applied to the remotely sensed imagery in order to improve confidence

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