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Impacts of selective logging on New Georgia Island, Solomon Islands evaluated using very-high-resolution satellite (IKONOS) data

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SUMMARY

Selective harvest has become a dominant method of commercial logging in tropical rainforests of the Asia-Pacific region. Although it has usually been recognized that this method minimizes the impact on forest because of the limited number of trees harvested and slight effects on growth of unharvested trees, recent reports suggest that its damage is potentially serious. This study aimed to evaluate the effects of a selective logging operation in 1993–1994 on customary land (2024 ha) of New Georgia Island, Solomon Islands. Geo-referenced IKONOS panchromatic (1-m resolution) and multispectral (4-m resolution) images from 2002 (the post-logging period) and aerial photographs (2.5 m pixels, original scale: 1:25 000) from 1991 (the pre-logging period) were analysed by means of supervised classification and on-screen visual interpretation, in association with detailed field observation. The area deforested by selective logging was 88 ha (95% confidence limits: 79–98 ha), accounting for 7.4% of the original forest and thus causing substantial damage.

Keywords: Asia-Pacific region, deforestation, remote sensing

INTRODUCTION

In tropical Asia-Pacific region, commercial logging was once conducted mainly in Peninsular Malaya and island South-east Asia, but the target areas have been extended to Papua New Guinea and the Solomon Islands since the 1960s because of resource depletion and governmental bans on log export from many Asian countries (Bennett 2000; Hviding & Bayliss-Smith 2000; Seymour & Dubash 2000). In the Solomon Islands, timber sales accounted for more than 50% of the total export and 20–30% of the total budget in the late 1990s (Department of National Development 1999), making the Solomon Islands the most log export-dependent country in the world (UNDP [United Nations Development Programme] *et al.* 2000). The annual volume of timber produced has exceeded the sustainable level since the early 1990s, reaching 75 000 m^3, three times that level, in 1997 (Department of National Development 1999; Bennett 2000). However, the impacts of the logging operations have scarcely been investigated, especially in terms of deforestation rate.

Selective logging, by which particular high-value species are harvested, has become a dominant style of commercial logging operation in the Solomon Islands and other Asia-Pacific countries (Collins *et al.* 1991). It has been recognized that this method minimizes intervention in to the forest because few trees are harvested and effects on growth of the remaining trees are slight (Collins *et al.* 1991; Grieser Johns 1997). Previous estimates of deforestation rate in the tropics have generally neglected the effects of selective logging (FAO [Food and Agriculture Organization of the United Nations] 2001, 2003; Achard *et al.* 2002; Fearnside & Laurance 2003). Recent studies, however, have suggested that these effects are potentially large enough to threaten the accuracy of conventionally estimated deforestation rates (Stone & Lefebvre 1998; Nepstad *et al.* 1999).

Remote-sensing imagery, with high consistency and accuracy, has been used to assess a variety of environmental changes (Mayaux *et al.* 1998; Achard *et al.* 2002). Satellite data, however, have seldom been applied to evaluation of the effects of selective logging because of difficulties in measurement of the small canopy gaps that are widely scattered in the forest (Stone & Lefebvre 1998; Asner *et al.* 2002). For this purpose, very-high-resolution satellite data is now available (Asner *et al.* 2002). IKONOS, a commercial satellite launched in 1999, provides a 1-m resolution panchromatic image and a 4-m resolution multispectral image; in fact, canopy gaps with narrow areas (for example <200 m^2) and roads of narrow width (for example 10 m) have been distinguished from the surroundings in Amazonian rainforest using the IKONOS resolutions (Read 2003; Read *et al.* 2003).

This study aimed to evaluate the impacts of selective logging on tropical rainforest of Western Province, Solomon Islands, using IKONOS data and aerial photographs acquired respectively 8 years after and 2 years before a logging operation in 1993–1994, and associated with detailed field observation.

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SUBJECTS AND METHODS

Western Province of the Solomon Islands

Of the 5475-km^2 land area in Western Province, which constitutes 19% of the whole land area of the Solomon Islands, 93.2% were covered with forest in 1960 (Ministry of Forest, Environment & Conservation 1995). Since commercial logging began in this country in the 1960s, the Western Province has been the major target (Rural Development Division 2001). The logging operations have been mainly performed on customary land that has been managed by traditional landowners and used by local people for slash-and-burn horticulture and gathering.

Like all islands of Western Province, our study area, New Georgia Island, was originally covered with evergreen tropical rainforest (Collins *et al*. 1991). The average maximum and minimum temperatures were 30.3°C and 24.2°C (in 1993), and the mean annual rainfall was 3458 mm, with little seasonal variation in the monthly amounts (averaging 225 mm in October to 390 mm in February), according to the 1987–1993 records from the nearest meteorological station at Munda, New Georgia Island . (Fig. 1; Statistics Office 1995).

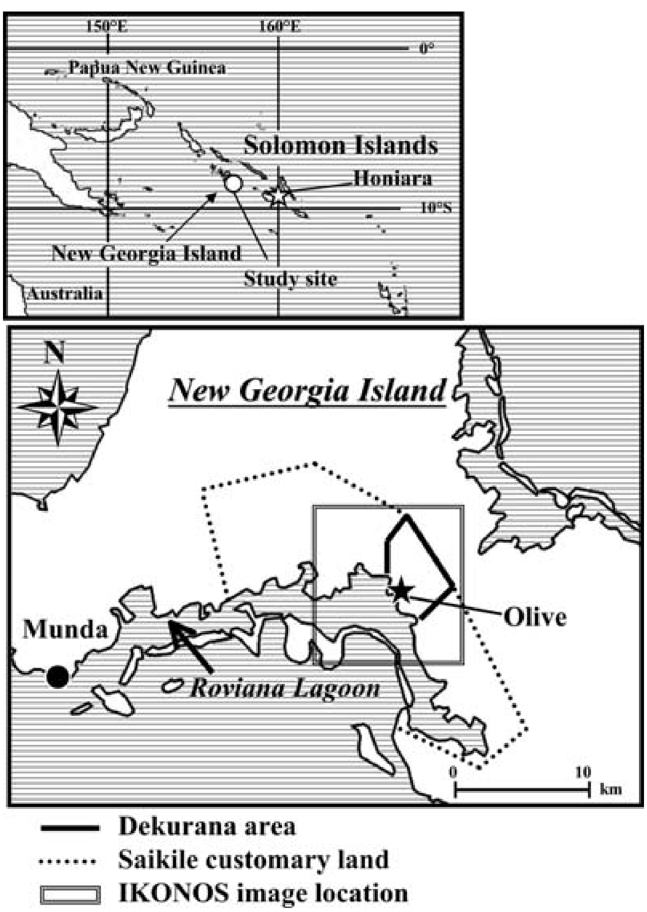

Figure 1 The location of Olive village, the Dekurana area and the Saikile customary lands.

Dekurana area

The 2024 ha study site in Dekurana is located in the southern part of New Georgia Island (Fig. 1). According to the 1:50 000 DOS 456 topographic map published in 1968 (Wall & Hansell 1975), Dekurana land below 360 m above sea level has gentle to moderate (<20°) slopes. Dekurana was once covered with tall canopy (30–40 m in height) lowland rainforest, including such species as *Calophyllum* spp., *Dillenia* spp., *Campnosperma brevipetiolata* Volk. and *Pometia pinnata* Forst., with an understorey of lower trees and palms. As a result of either human activities or natural phenomena or both, forests are patchily broken into gaps covered by lower trees and shrubs, although herb layers occur irregularly and erratically (Hancock & Henderson 1988).

Dekurana is the territory of Olive village (8° 26.94′ S and 157° 55.18′ E) and constitutes part of the customary land owned by the Saikile tribe. The inhabitants of Olive (357 in 49 households in January 2001) have been allowed to use the whole Dekurana customary land for horticulture and gathering of wild plants, under the control of the chief of the Saikile tribe. In the 1980s, they began cultivation of cash crops such as cacao in the garden areas, but such activities did not provide the villagers with adequate economic profits and thus were all but discontinued by the mid-1990s. Saikile people, including Olive villagers, established the Saikile Development Company to conduct portable saw-milling in the mid-1980s, but this activity also ceased by the mid-1990s.

In 1993 and 1994, the Dekurana area was selectively logged. In the first year, the main roads, 10–15 m in width, were constructed for transportation of logs by trailers. In the second year, narrower roads, called ‘sub-roads,’ about 10–12 m in width, were made, running from the main roads into the forest. Tree harvesting with chainsaws then began in areas usually within 300–400 m from the sub-roads. Bulldozers dragged the felled logs; at sites far from the sub-roads, however, the logs were skidded to the spots where bulldozers were available. The major targets were canopy-top tree species with high commercial values, such as *Calophyllum* spp., *Pometia pinnata* Forst., *Dillenia* spp., *Campnosperma brevipetiolata* Volk. and *Vitex cofassus* Reinw. ex Blume, but almost all harvestable trees were logged. Consequently, many canopy gaps of various sizes appeared, which looked like holes in the satellite image. These gaps were generally less than 200 m^2 in size, though there were larger gaps of 1000 m^2 or more in areas where the harvested logs had been dragged by bulldozers, for instance where the route taken by the vehicle zigzagged. Any gaps, which became bare soil or grasses/shrubs, were confirmed by direct on-site observation and in the satellite images taken in 2002.

Since 1997, Olive villagers have reforested the commercially-logged areas with fast-growing trees. In 2002, the major land cover of the Dekurana area consisted of the village settlement, the villagers' horticultural gardens and reforested areas, and forest, most of which had been selectively logged. The spatial pattern of the Dekurana land was similar to that of most customary land in Western Province (Hviding &

Bayliss-Smith 2000). Since there was no land with steep slopes, where the land cover would be obscured by shadows, the Dekurana land was suitable for satellite image analysis.

Field survey

Field surveys were conducted from January–October 2001 and from May–June 2002. Throughout the survey periods, one of us (Takuro Furusawa) stayed in Olive village, observed and participated in village activities, such as horticulture and collection of forest resources, and inspected the entire Dekurana area, identifying the land use and cover, clarifying historical changes and associating these with local place names; the last was usually done with assistance of the villagers, using the local Roviana language. Special attention was paid to recording all lands where logging had been carried out; Takuro Furusawa identified these areas by referring to villagers' knowledge, as well as observing evidence such as sawn tree trunks and abandoned roads. A GPS (global positioning system) was not used in this process because of its low accuracy in the forest.

We determined the ground control points (GCPs) using a GPS system (Trimble Ltd.), equipped with ProXR antenna and 4600LS, for collection of, respectively, rover and base data. The differential correction was performed using Pathfinder Office version 2.70, the maximum error being < 0.6 m (Trimble Ltd, unpublished data 2004). Thus 32 GCPs, such as edges of dwellings, wharves and bridges, were identified for use in image geo-referencing.

Satellite data and aerial photographs

The IKONOS data (11 × 11 km; Space Imaging processing level: standard geometrically corrected) used in this study were acquired on 13 July 2002 (acquisition attributes: sun azimuth = 39.9°, sun elevation = 50.7°, collection azimuth = 56.4°, and collection elevation = 60.6°. Both the multispectral image with 4-m pixels, consisting of four bands for blue (0.45–0.52 m), green (0.52–0.60 m), red (0.63–0.69 m), and near-infrared red (0.76–0.90 m), and the panchromatic image with 1-m pixels were analysed. Of the five aerial photographs analysed, two were taken on 9 October 1991 and three were taken on 13 October 1991; these were kept at the Department of Lands, the Ministry of Land and Housing of Solomon Islands, in 2.5-m pixel digitized form (original scale 1:25 000). We used ERDAS Imagine version 8.6 (ERDAS Ltd) for all image analyses.

All satellite data and aerial photographs were geo-referenced by means of a nearest-neighbour resampling method. Since a detailed topographic map was not available, this procedure was based on the GCPs collected in the field (Pahari *et al.* 2002). First, an IKONOS panchromatic image was geo-referenced, based on the longitude and latitude of each GCP. Next, an IKONOS multispectral image and five aerial photographs were registered onto the geo-referenced panchromatic image. In the process of geo-referencing, the GCPs were deleted one by one in descending order of magnitude of contribution to the error until the root mean square error (RMSE) was reduced to less than 1 pixel. We thus constructed a mosaic image for the whole study area in 1991.

Evaluation of selective logging and clear cutting

IKONOS data in 2002

We analysed the IKONOS image by digital classification of land cover, followed by on-screen visual interpretation of land uses of the deforested lands; land cover refers to the object that covers the surface of the earth in terms of its physical structure, while land use refers to the intended use-pattern of the land, taking into account not only the current status, but also the latest changes (Longley *et al.* 1999).

For the digital classification, land cover was divided into six classes: (1) tree crown (canopy), including that of mature trees, such as coconut palms and timber trees, planted by the villagers, (2) grass/shrub with or without small standing trees, (3) bare soil, (4) house (roof), (5) water and (6) cloud; cloud cover is not physically 'land cover', but was considered as a land-cover class in this process. We selected 86 polygonal training fields, each including more than 100 pixels, which included the respective land-cover features. These training fields for each class involved those on shaded areas, but our field observation identified each pixel as one of the six classes. A supervised classification procedure (the maximum likelihood algorithm) was then performed, using these training fields. Accuracy of the classification was assessed by on-screen visual interpretation of the panchromatic image in 512 randomly-selected pixels. The pixels, which were identical in both visual interpretation and supervised classification, accounted for 94.9% of the selected pixels. At this stage, however, it was revealed that the spectral pattern of the house (roof) could not be distinguished from cloud cover; 90.9% of the pixels (10/11) assigned to house by the supervised classification were visually interpreted as cloud. We therefore decided to combine these two classes; it was estimated that true house (roof) cover amounted to 3 ha (0.02%) and 1 ha (0.05%), respectively, in the image and in the Dekurana area as a whole.

The classified image, hereafter called the 'land cover map', was analysed for the entire Dekurana area; since approximately 35% was covered by cloud, the remaining area (1316 ha) was targeted. However, exclusion of areas in shadow did not seriously bias the results because the land-cover/land-use patterns were almost identical in the cloud-covered area and the remainder; for instance, tree crown cover, excluding cloud, house and water, accounted for 74.8% of all Dekurana land and 76.7% of the whole IKONOS image of 11 × 11 km.

After the land cover map of Dekurana area had been made, land areas either cleared or logged were estimated for 1000 pixels randomly selected from 206 952 pixels, which were classified as grass/shrub or bare soil by the supervised classification; it is noted that no specific spectral pattern corresponded to any particular land use (for example canopy gaps caused by the selective logging) so that digital classification was not applicable to this process. The land use in each pixel was identified by on-screen visual interpretation of the panchromatic image, with reference to the field observations. Because the target area was originally covered by dense forest canopy (Collins *et al*. 1991), land cover of grass/shrub or bare soil in the images had evidently been cleared or logged by the company or villagers. In this way, eight land-use classes were identified, namely (1) canopy gap produced by selective logging and (2) logging road and camps, both of which were attributed to company logging; (3) horticultural gardens, (4) settlements, (5) timber plantations and (6) portable saw-mills, all of which resulted from villagers' activities; and (7) canopy gaps caused by phenomena such as cyclones and (8) bare land along the coast, both of which were naturally occurring. All sampled pixels, except the following two, were successfully assigned to one of these classes by field observation. When on-screen visual interpretation was not possible because of cloud cover, such a pixel was classified as land unable to be identified. The error in the supervised classification was regarded error.

Despite the fact that there were small scattered forest gaps, those caused by logging were distinguished from those by natural phenomena, based on field observation at the locations of gaps caused by logging. In this process, the gaps along sub-roads or in logging areas were judged to have originated from commercial logging, even though they might have been made after the operation.

We estimated the land area in each class with 95% confidence limits (CL), based on the number of pixels counted, following standard statistical procedures (Armitage *et al.* 2002).

Aerial photographs in 1991

We made a land-use/land-cover map in 1991 based on on-screen visual interpretation of aerial photographs. For this purpose, a digital classification was not applicable, because different land uses/land covers were unable to be properly distinguished in the photographs, which were taken without sensing in the near-infrared red band. The land was thus divided into four classes, namely forest, horticultural gardens including fallow gardens with grass or shrub grown, settlements and other cleared lands, and water. Since cloud cover (7.7%) was concentrated in the natural forest zone, all cloud-covered areas were interpreted as forest.

Land-cover/land-use change from 1991–2002

The land use/land cover in 1991 was compared with that in 2002, using the 1000 pixels sampled in the IKONOS data analyses. Land areas newly cleared or logged during the 11-year period were estimated with 95% confidence limits. The areas of tree crowns and natural canopy gaps, which were not distinguished from each other, were regarded as forest area in 1991, while the added areas of tree crowns identified by the digital classification and canopy gaps identified by the visual interpretation were regarded as forest in 2002. Net forest area change was calculated as (forest regrowth area in each land use class in 1991) – (area deforested for each land use class in 2002).

Table 1 Land cover estimated by a supervised classification of an IKONOS multispectral image for Dekurana in 2002. *High proportion of errors in classification occurred for the house and cloud cover; the land area of house cover by on-screen visual interpretation was 1 ha.

Land cover	*Area (ha)*	*Proportion (%)*
Tree crown	983	48.58
Grass and shrub	261	12.89
Bare soil	70	3.47
Water	1	0.07
Cloud and house*	708	35.00
Total	2024	100

Table 2 Land use of 331 ha of non-forested land (grass/shrub and bare soil cover) in the Dekurana area in 2002. *Land unable to be identified refers to pixels obscured by cloud.

Land use	*Proportion in non-forest land in 2002 (%)*	*Area (ha) in 2002 (95% CL)*
Lands deforested by the foreign company		
Logging gap	27.3	90 (81 : 100)
Road and camp	2.7	9 (6 : 13)
Lands deforested by the villagers		
Garden	17.9	59 (52 : 68)
Settlement	6.1	20 (16 : 26)
Timber plantation	0.4	1 (0 : 3)
Portable saw-mill	0.4	1 (0 : 3)
Other non-forested lands		
Gap	26.5	88 (79 : 97)
Coastal land	0.8	3 (1 : 5)
Lands unable to be identified*	8.4	28 (22 : 34)
Error	9.5	31 (26 : 38)
Total	100	331

RESULTS

Land cover/land use in 2002

In 2002, 983 ha had canopy cover and 331 ha was grass/shrub or bare soil (Table 1). Of the latter, the bulk of artificially-changed areas were gaps attributable to the company's selective logging (90 ha, 27.3% of grass/shrub and bare soil cover) and gardens (59 ha, 17.9%) (Table 2). Comparing these two classes based on their 95% confidence limits, the impact of the selective logging was significantly larger than that of horticulture.

Table 3 Land use/land cover in 2002 and its corresponding land use in 1991 for the Dekurana area. 95% confidence limits given only for land covered by grass/shrub or bare soil in 2002.

Land cover/land use in 2002	*Land use (ha) in 1991 (95% CL)*		
	Forest	*Garden and fallow*	*Settlement and other cleared lands*
Forest			
Tree crown	948	30	5
Gap	88 (79 : 97)	0	0
Lands deforested by the foreign company			
Logging gap	88 (79 : 98)	2 (1 : 4)	0
Road and camp	9 (6 : 13)	0 (0 : 2)	0
Lands deforested by the villagers			
Garden	49 (42 : 57)	10 (7 : 14)	0
Settlement	9 (6 : 13)	2 (1 : 4)	10 (6 : 14)
Timber plantation	1 (0 : 3)	0 (0 : 2)	0
Portable saw-mill	0	0	1 (0 : 3)
Total	1192	44	16

Table 4 Net rate of change of forest area from 1991 to 2002; negative scores imply net deforestation. *Regrowth areas for the land uses which arose after 1991 (i.e. selective logging, road and camp, and timber plantation) were not estimated.

Land use	*Deforested area (ha; 95% CL in paranthesis)*	*Regrowth area* (ha)*	*Net forest area change*	
			(ha; 95% CL in paranthesis)	*(%; 95% CL in paranthesis)*
Lands deforested by the foreign company				
Logging gap	88 (79 : 98)	—	−88 (−79 : −98)	−7.42 (−6.66 : −8.21)
Road and camp	9 (6 : 13)	—	−9 (−6 : −13)	−0.72 (−0.47 : −1.05)
Lands deforested by the villagers				
Garden	49 (42 : 57)	30	−20 (−12 : −27)	−1.64 (−1.04 : −2.29)
Settlement	9 (6 : 13)	5	−4 (−1 : −8)	−0.30 (−0.05 : −0.64)
Timber plantation	1 (0 : 3)	—	−1 (−0 : −3)	−0.08 (−0.02 : −0.24)
Portable saw-mill	0	0	0	0.00
Total	156 (146 : 167)	35	−121 (−111 : −132)	−10.17 (−9.30 : −11.04)

Deforestation from 1991 to 2002

Between 1991 and 2002, forest area cleared or logged by the company and the villagers amounted to 156 ha, of which 88 ha (56.4%) were attributable to selective logging by the company (Table 3). Forest clearance to horticultural garden, which had more profound effects than any other of the villagers' activities, had less significant impact than commercial logging. The 59 ha (95% confidence limits 52–68 ha) forest area cleared by all villagers' activities was significantly smaller than that attributed to commercial logging, even if the forest cleared for construction of roads and campsites was excluded. In contrast, all forest cleared for horticultural gardens, timber plantation and settlement by the villagers and for roads and camps by the logging company amounted to 68 ha (60–77 ha), being significantly smaller in area than the forest cleared by logging. Also, 35 ha of land that had been cleared for horticulture and settlement in 1991 had naturally regenerated to forest by 2002.

Of the forest, 7.4% (6.7–8.2%) disappeared because of selective logging (Table 4). Other activities played less significant roles in the change; for instance, the contribution of gardens was only 1.6% (1.0–2.3%; Table 4).

DISCUSSION

Particular attention was paid to the impacts of selective logging on forest cover for eight years after operation. The highlight of this study of changes in forest on customary land in the Solomon Islands subject to commercial logging was detection of canopy gaps caused by selective logging, despite the suggestions that such gaps become closed over periods much shorter than eight years (Stone & Lefevbre 1998; Asner *et al*. 2002).

In this study, very accurate geo-referencing was useful for comparisons of pixels between the images acquired at

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different times. Methodologically, there was a possibility that the pixels with <1-pixel RMSEs were not identical between the IKONOS images and the aerial photographs, particularly when they were located near the borders between different land-cover/land-use classes in 1991. However, such biases were minimized, firstly because in 1991 the land cover/land use was quite simple (95.3% of land was covered by forest) and, secondly, because the pixels were randomly sampled and thus few of them were located in such borders.

In 2002, 7.4% of the forest area consisted of gaps caused by commercial logging in 1993–1994. From the viewpoint of the forest ecosystem, the trees growing in the gaps were in the early stage of regeneration. The regeneration of Solomon Islands forests largely depends on the magnitude of disturbance (Whitmore 1989; Burslem & Whitmore 1999). According to 20 years' observation of forests on Kolombangara Island, neighbouring New Georgia, in cases of extensive and large disturbances (such as cyclone Isa), the canopy was replaced by light-demanding pioneer species, which were newly germinated and grew to the mature stage after several decades; in usual cases, the canopy was quickly replaced by shade-tolerant species, which had already grown under the canopy top (Whitmore 1989, 1998). Since such shade-tolerant trees were felled in our study site during the selective logging operation, the gaps we observed should be the former type. Our field observations confirmed that light-demanding trees grew in the gaps, though they were still short compared to the common growth pattern. For instance, the most popular light-demanding fast-growing species, *Campnosperma brevipetiolata* Volk., exceeds 40 m height at its maturation, and grows to 15–17 m tall at 8–9 years of age according to the governmental reforestation projects in Solomon Islands (Marten 1980). However, in the study site, the height of eight-year-old trees of the same species was approximately 10 m.

Vegetation characteristics in the study area, or in the Solomon Islands as a whole, are also relevant; in particular, there are only a limited number of species with high commercial values in a global timber market. According to the governmental record of timber volumes exported in 1989 (Forestry Division 1989), one-third were 'mixed' species without the timber codes. Because of a shortage of highly valuable tree species, various kinds of trees, with less regard to the economic values, were felled. As indicated by Whitmore (1998), the severity of damage on forest depends on the number of trees felled per unit of area. An important characteristic of the operation method in the Solomon Islands was the extraction of trees by bulldozers, which depleted the numbers of seedlings over a wide area (Whitmore 1998).

Field observation, in association with the villagers' knowledge, clarified whether the gaps in 2002 were located in and near the logging operation sites; as mentioned previously, these gaps were recognized to have occurred as a result of commercial logging. Such gaps were formed because the fallen tree trunks were frequently left after the operation and/or because the trees, which were damaged during extraction of other harvested trees, died thereafter. Such collateral damage is common in logging operations in Solomon Islands and in some South-east Asian countries (Grieser Johns 1997). Although further studies are needed to systematically elucidate such 'side effects' of commercial logging, this study has provided evidence supporting the suggestion that the impacts of selective logging have been neglected but are potentially large enough to threaten the validity of global deforestation estimates (Nepstad *et al*. 1999; UNDP *et al*. 2000).

In contrast to commercial logging, deforestation by the villagers' traditional activities, especially shifting cultivation, produced limited effects. Their shifting system has been based on the rotational land use for cultivation for a few years followed by a fallow period of 13–14 years and, consequently, the cultivated lands tend to regenerate to secondary forest within several years or a decade (Furusawa *et al*. 2002). In the study area, the villagers had also initiated a reforestation programme for timber plantation, but this activity was limited to a small area, although fast-growing species (such as *Eucalyptus deglupta* BL.) planted in 1997 grew enough to cover the cleared land.

It is worth considering forest clearance in Western Province as a whole, the total forest area of which is 473 936 ha. In 1991, 38.4% of the forests were not subject to commercial logging, although all such lands would be logged sooner or later (Ministry of Forest, Environment & Conservation 1995). If we assume that the present results applied to the entire forest area, 13 517 ha (2.7% of the total) would disappear because of selective logging for commercial purposes. In conclusion, this study highlights that degradation by selective logging is counter to forest conservation in the Solomon Islands.

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