Nest-site selection of New Zealand Falcons (*Falco novaeseelandiae*) in plantation forests and the implications of this to forestry management

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Abstract. This study investigates the factors that determine nest-site selection by New Zealand Falcons (*Falco novaeseelandiae*) in a plantation pine forest. Selection was examined by measuring habitat and forestry management variables at actual nesting sites and randomly selected sites in the forest. Nesting sites were located on the ground in pine stands up to 5 years old, with unplanted and 1-year-old stands of pine selected preferentially for nesting. Overall, 54\% of pairs nested in the same stand of pines in a subsequent year, whereas 44\% moved to a stand of the same age or younger and 2\% moved to older stands. Falcons chose nesting sites close to older pine trees and with cover over the scrape. New Zealand Falcons benefit from clear-fell harvesting that creates a mosaic of stand ages across a plantation. This mosaic provides both suitable nesting sites and an abundance of prey. This threatened species benefits from felling plantation forests in fairly small, discrete stands.

Introduction

In order to manage landscapes effectively for the conservation of a species, it is important to understand what factors are most important in the selection of nesting sites at the scale of landscape, home-range and nesting site. Although there is a good understanding of the broad habitat requirements of the New Zealand Falcon (or Karearea, *Falco novaeseelandiae*) on a landscape scale (Fox 1977), we still know little about the factors involved in selection of nesting sites at the finer scales (Barea et al. 1997; Lawrence 2002). There are three forms of the New Zealand Falcon (Fox 1977) all of which are considered threatened (Miskelly et al. 2008). The bush form of the New Zealand Falcon, the subject of this study, is a forest falcon found over much of the North Island and extending to the north-west of the South Island. It is thought to be ecologically distinct from the other forms of the Falcon (Fox 1977) and has been the subject of little research (Fox 1977; Lawrence and Gay 1991; Barea et al. 1997; Stewart and Hyde 2004).

The bush form of the Falcon has traditionally nested in the podocarp and southern beech forests typical of the North Island of New Zealand. Typical nesting sites include the ledges of limestone bluffs, on the ground in beech forests and within the epiphytes of large trees in podocarp forests. In post-colonial times the ecology of the New Zealand Falcon has changed dramatically, with large areas of their traditional forest habitat being cleared, the introduction of mammalian predators, and significant changes in the numbers and suites of species available as prey. The contribution of pine plantations to indigenous biodiversity in New Zealand is becoming well understood, with a wide diversity of indigenous flora and fauna existing in plantation forests (Clout and Gaze 1984; Ogden et al. 1997; Brockerhoff et al. 2003; Pawson et al. 2010).

We describe New Zealand Falcon nesting sites in a managed plantation of exotic pines and describe how habitat, breeding dispersal and forestry management influence choice of nesting site in this habitat. We tested the hypothesis that nest-site selection was non-random and attempted to identify habitat characteristics that would allow us to make management recommendations to enhance the breeding population. As exotic pine forest is now recognised as a major habitat for this threatened species (Stewart and Hyde 2004; Addison et al. 2006; Pawson et al. 2010), appropriate forestry management is important to its conservation.

Methods

The study was conducted in the North Island of New Zealand in Kaingaroa Forest (Fig. 1), a single block of 180 000 ha, mostly of Radiata Pine (*Pinus radiata*). In New Zealand, stands of Radiata Pine mature in 25 to 35 years and are generally felled at this time. The trees are harvested in discrete blocks, or compartments, creating a mosaic of differently aged stands. The edges of each stand are well defined where they change between blocks of uniformly aged pine trees (Fig. 1).

Nesting sites of New Zealand Falcons were surveyed over three breeding seasons (September to March) from 2003 to 2006. A broad selection of factors designed to describe the structural variability between pine stands were measured around each nest-site and around randomly selected sites within the pine forest.

Adult New Zealand Falcons were trapped using Balchatri traps and Dho Gaza nets (Bloom 1987), and fitted with individual
combinations of colour-bands. Chicks, where possible, were banded on the nest; otherwise they were trapped after they were 50 days old. This project was endorsed by the Animal Ethics Committee of Massey University (01/24 and 03/105) and the Raptor Association of New Zealand (permit number 0285).

Location of nesting sites

Previous work in Kaingaroa Forest suggested that Falcons nest on the ground within stands of pines, mainly, but not solely, stands <4 years old (Stewart and Hyde 2002, 2004; Addison et al. 2006; Wingspan Birds of Prey Trust, unpubl. data), so we concentrated our survey efforts on these stands. Plantation pines offer no opportunities for Falcons to nest off the ground. Forestry workers are attacked at a distance of 100 m or more from a pair of ground-nesting Falcons and thus quickly become aware of the breeding birds. In Kaingaroa Forest all the pine stands <4 years old were identified each breeding season. These young stands were intensively walked to elicit defensive behaviour and to listen and watch for other characteristic Falcon breeding behaviour. Typically each forestry compartment of 1 km² was traversed with four transects of 1 km each, for a total of 4 km. The same search intensity was employed between compartments of differing size and age (see below) and the same survey effort and technique was used each season.

Age of nest-stands

In order to compare use with availability, and hence selection, we recorded the age of each pine stand where nests were located and the number of each age-class of stands that was available each breeding season. Where nests were located on the border between two stands, the younger stand age was used. Use was compared with availability using a Kolmogorov–Smirnov two-sample test.

Size of nest-compartments

A clear-felled compartment was defined as the discrete area of trees <4 years old surrounding a nest. The sizes of the clear-fell compartments used for nesting were compared to those available.
each season using a Kolmogorov–Smirnov two-sample test. To avoid pseudo-replication, we used only data from the 2005–06 breeding season for this analysis.

**Nesting habitat and forestry management**

Habitat variables were measured at each nest-site during the 2004–05 and 2005–06 breeding seasons. These included broad measurements of habitat within 50 m of the nest and more detailed measurements within 1 m of the nest-scrape (Table 1). Data on forestry management for each nest-compartment were also collected, including details of machine operations, spray regimes and predator control (Table 1). In order to determine the variables that differed between compartments where Falcons nested, and compartments where they did not, and to investigate whether Falcons nested at random within these compartments, these variables were also measured at randomly selected sites within the plantation. These randomly selected sites (RSSs) were chosen throughout the forest within stands <4 years old where Falcons were absent.

In order to describe nesting sites on a broader scale, hypothetical home-ranges of 9.23 km², representing the mean adult male home-range in Kaingaroa Forest (Seaton 2007), were constructed centring on each nest-site and RSS. Ages of pine stands were classified (<4 years old, 4–9 years old, 10–19 years old, and >20 years old) and the area of each age-class within each home-range was calculated (Fig. 2).

We used t-tests to assess differences between home-ranges centred on nests and RSSs. To further analyse the choice of nesting sites by Falcons, we used a step-up binary logistic regression to identify variables of potential importance within a single model (SPSS for Mac, ver. 17.0.0., 2008, SPSS Inc., Chicago, IL). The binary independent variable was actual nest-site versus RSS, and the 29 habitat variables were the predictors. The significance of each predictor variable was Bonferroni corrected.

### Breeding dispersal

After the first breeding season, we recorded colour-bands of Falcons to assess individual movements and pairings between breeding seasons.

### Results

#### Location of nesting sites

The number of nesting New Zealand Falcon pairs increased in the study site from 20 in 2003 to 36 in 2006. The mean distance between nearest nests decreased from 4.48 km in 2003, to 3.73 km in 2004, to 3.25 km in 2005. The closest nests, which were located in the third breeding season (2005–06), were only 0.97 km apart.

Within the forest, New Zealand Falcon nesting sites were similar to one another, with most nests being located on the ground, among pine slash (pine twigs, branches and logs left over after tree felling; Table 1). However, where stands <4 years old bordered indigenous forest (on the edge of Kaingaroa Forest), Falcons nested in the large epiphytes in emergent indigenous trees and not on the ground. No pairs of Falcon were located breeding on the ground in pine stands <4 years old when the stand was bordered by indigenous forest.

#### Age of plantation stands

The availability of stands <4 years old fluctuated spatially and temporally as stands became older and new stands were created by felling each year (Table 2). In the third breeding season, Falcons in Kaingaroa Forest had 172 discrete stands <4 years old available for nesting. From the available stands, Falcon pairs selected unplanted stands and those containing pine trees 1 year old or less, over pine stands containing trees 2 and 3 years old (Kolmogorov two-sample test $K = 1.49, P < 0.05$) (Table 1).

#### Size of plantation stands

New Zealand Falcons nested in stands of pine between 0.17 km² and 24.14 km². More Falcon nests were located in small stands

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**Table 1. Characteristics of New Zealand Falcon nesting sites (n = 63) and randomly selected sites (n = 49), and tests of differences between them**

Significance was tested using a two-sample t-test (with significance levels given for individual tests). Thirty-three variables were tested, but only those with a significance level of $P < 0.10$ are reported here. To make Bonferroni corrections for the 33 tests at the 0.05 level, significance must be $P < 0.0015$. Variables significant at $P < 0.0015$ are highlighted in bold.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>Nesting site (nest)</th>
<th>Randomly selected site (RSS)</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Minimum</td>
<td>Maximum</td>
<td>Minimum</td>
</tr>
<tr>
<td>Area of ground within 50 m of nest or RSS covered with pine slash (%)</td>
<td>31</td>
<td>5</td>
<td>70</td>
<td>23</td>
</tr>
<tr>
<td>Area of ground within 50 m of nest or RSS covered with non-pine vegetation (%)</td>
<td>33</td>
<td>1</td>
<td>95</td>
<td>44</td>
</tr>
<tr>
<td>Height of pines in the youngest compartment adjacent to the compartment with the nest or RSS (m)</td>
<td>1</td>
<td>0</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Area of log loading zone within 50 m of the nest or RSS (%)</td>
<td>1</td>
<td>0</td>
<td>19</td>
<td>3</td>
</tr>
<tr>
<td>Area of pine 4–9 years old within 1.72 km of nest or RSS (km²)</td>
<td>2</td>
<td>0</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Area of pine &gt;20 years old within 1.72 km of nest or RSS (km²)</td>
<td>2</td>
<td>0</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Time since fertiliser applied (months)</td>
<td>3</td>
<td>0</td>
<td>58</td>
<td>0.02</td>
</tr>
<tr>
<td>Proportion cover over nest or RSS (%)</td>
<td>66</td>
<td>0</td>
<td>100</td>
<td>19</td>
</tr>
<tr>
<td>Distance to the nearest stand edge (m)</td>
<td>113</td>
<td>5</td>
<td>400</td>
<td>175</td>
</tr>
<tr>
<td>Height of pines at nearest edge (m)</td>
<td>20</td>
<td>0.2</td>
<td>30</td>
<td>13</td>
</tr>
<tr>
<td>Mean height of vegetation &lt;1 m from the nest or RSS (m)</td>
<td>0.3</td>
<td>0</td>
<td>1</td>
<td>0.7</td>
</tr>
</tbody>
</table>
<4 km$^2$ than in larger stands. However, there were more small stands than large stands available in the forest and small stands <1 km$^2$ were used less than expected based on their availability. Overall, when allowing for the difference in availability of stand sizes, there was no difference between the number of stands of each size available and the number of each size used for nesting by New Zealand Falcons (Kolmogorov two-sample test $K = 0.77$, n.s.) (Fig. 3), indicating that no particular size of stand was being selected.

**Habitat and forestry management**

Nesting sites and RSSs had similar forestry management and habitat characteristics, but two variables explain most differences
between them (Table 3). Nesting sites had more cover over the scrape and taller pines at the stand edge nearest the nest (where a stand edge is the border between two stands differing in height by 4 m or more). The mean cover over nest-scrapes was 66%, whereas at RSSs the mean cover was 19%. For nesting sites, the mean heights of pines at the nearest edge were 20 m, compared to 13 m for RSSs (Table 1). Over 60% of nests were located <100 m from the nearest stand edge, and over 90% were located <200 m distant (n = 63; Fig. 4).

Control of plantation pests was carried out throughout the forest. The most common control method was use of 1080 poison (sodium monofluorooacetate). Although this targeted plantation pests (Common Brushtail Possums (Trichosurus vulpecula) and European Hares (Lepus europaeus)), some rats (Rattus spp.) were also killed, and some secondary poisoning of mustelids and feral Cats (Felis catus) can also occur (Gillies and Pierce 1999). No significant difference was recorded between nesting sites and RSSs in the time since 1080 was applied (P = 0.29) (see Table 1). For the other management variables measured, we found no significant difference between nest-sites and RSSs (Table 1).

Breeding dispersal

We colour banded 174 New Zealand Falcons in Kaingaroa Forest during this study, and another 28 Falcons had previously been banded by the Wingspan Birds of Prey Trust. This comprised 28 adult males, 27 adult females, 73 nesting males and 74 nesting females. During the study, 63 banding recoveries were made, of which 19 were males and 44 were females.

The mean distance moved by individuals between subsequent nesting attempts was 0.91 km (n = 48), ranging from 0 to 4.24 km. One pair nested in the same scrape for three consecutive seasons and a further two pairs for two consecutive seasons. All other pairs used a nesting scrape once.

Falcons breed in younger stands either by nesting in the same stand as the previous year (54%), or by moving to a younger stand or another of the same age (44%) (n = 48; Table 4). Only one pair of Falcons was recorded moving to an older stand between breeding seasons. Overall, 31% of pairs nested in stands aged <1 year old, 25% in stands 1 year old, 24% in stands aged 2 years old, and 21% in stands 3 years old (n = 84; Table 2). Of those that moved to younger stands, 35% moved to stands that had not been planted or were planted only the previous winter (n = 48). Of those pairs that remained within the same compartment between breeding seasons, 25% remained in stands 1 year old, 23% in stands 2 years old, but only 6% in stands 3 years old (n = 48).

Overall, 80% of pairs remained together to attempt to breed in the following breeding season (n = 48). In 12% of nesting

Table 2. The proportion of New Zealand Falcon nests found in each age-class of stands of pine (%), and the proportion of stands of that age-class available, for three breeding seasons and for the study combined

<table>
<thead>
<tr>
<th>Age of stand (years)</th>
<th>2003–04 Proportion of nests (%)</th>
<th>2004–05 Proportion of nests (%)</th>
<th>2005–06 Proportion of nests (%)</th>
<th>Total Proportion of nests (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Proportion available (%)</td>
<td>Proportion available (%)</td>
<td>Proportion available (%)</td>
<td>Proportion available (%)</td>
</tr>
<tr>
<td>&lt;1</td>
<td>35</td>
<td>47</td>
<td>44</td>
<td>42</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>29</td>
<td>25</td>
<td>33</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>14</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>11</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>n</td>
<td>20</td>
<td>28</td>
<td>36</td>
<td>84</td>
</tr>
</tbody>
</table>

Fig. 3. The percentage of New Zealand Falcon nests located in each stand area-class in 2005–06 (n = 36) and the percentage availability of stands <4 years old in each area class in 2005–06 (n = 312).

Table 3. Variables discriminating between randomly selected points and nesting sites in stands of pine between 0 and 3 years old

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>s.e.</th>
<th>Wald</th>
<th>d.f.</th>
<th>P</th>
<th>Exp(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover over scrape (%)</td>
<td>0.037</td>
<td>0.0073</td>
<td>25.32</td>
<td>1</td>
<td>0.000014</td>
<td>1.037</td>
</tr>
<tr>
<td>Height of pines at nearest edge (m)</td>
<td>0.097</td>
<td>0.0309</td>
<td>9.82</td>
<td>1</td>
<td>0.050</td>
<td>1.102</td>
</tr>
<tr>
<td>Constant</td>
<td>-2.778</td>
<td>0.6283</td>
<td>19.56</td>
<td>1</td>
<td>0.00028</td>
<td>0.062</td>
</tr>
</tbody>
</table>
since the early 1940s (Ryder 1948; Weeks 1949; Buddle 1953; et al. 2008). Prey abundance is promoted by the highly heterogeneous landscape of differently aged stands, whereas availability of prey is high as a result of the abundant edge habitat, created by clear-felling fairly small, discrete, blocks of forest. 

New Zealand Falcons have been observed in pine plantations since the early 1940s (Ryder 1948; Weeks 1949; Buddle 1953; Johnson 1953; Gibb 1961; Edgar 1963; Jackson 1971; Stewart and Hyde 2004), yet only Ryder (1948) reports Falcons nesting in this habitat before 1994. The paucity of early records of nesting suggests that the current high densities of Falcons in Kaingaroa Forest are a recent phenomenon. The steady increase in numbers of Falcon that we recorded in this study further supports this suggestion. Considering the large amount of suitable breeding habitat remaining in Kaingaroa Forest, further increases seem likely. The extent of those increases will depend on the size of clear-felled compartments, levels of local heterogeneity of stand ages, and continued availability of prey. Although pairs of Falcons did not select small clear-felled areas, large areas (of trees of similar age) are unlikely to hold high densities of Falcons because they have little edge habitat. We are unable to define an optimal size of stand or clear-felled compartment, but suggest that maintaining high local heterogeneity of stand ages over the whole plantation will promote high densities of New Zealand Falcons in pine plantations.

**Location of nesting sites**

Optimal foraging theory predicts that individuals should nest close to their food source (Pyke et al. 1977). This may account for nesting sites being located along the borders between young and mature pine stands as the highest prey abundances occur along these edges (Seaton et al. 2008). This may be particularly attractive to females, enabling them to take advantage of any hunting opportunities that may arise while still being able to brood and defend the nest.

Although providing an abundance of prey, the edges of mature stands may also aid in defence of nests by providing a vantage point from which to observe the approach of potential predators. Additionally, edges of stands could act as shelter from bad weather, although the position of older stands relative to nesting sites and the prevailing weather does not seem to indicate this.

Nesting opportunities in plantation forests are limited to the ground because plantation trees lack the epiphytes, tree cavities and snags found in indigenous podocarp forests (Barea et al. 1997; Lawrence 2002; Stewart and Hyde 2004). Kaingaroa Forest also lacks cliffs suitable for nesting, which are used in other habitats (Fox 1977). Vegetation cover increases with age of stands as plants colonise the bare ground between the pine trees (Allen et al. 1995). This reduces the availability of ground nesting space, making older stands unsuitable for nesting. Stands of pine <1 year old have very little vegetation cover after desiccant spray operations (Maclaren 1996) and were preferentially selected for nesting over those only 1–2 years older. Decreased vegetation cover in the younger stands could explain the preference. Hunting conditions may be more difficult with increased vegetation cover as prey are better able to seek cover (Suhonen et al. 1994) and nests may be more prone to predation as increased vegetation provides cover for potential predators to approach without risk of being killed themselves.

**Forestry management**

Forestry operations that leave pine slash (pine twigs, branches and logs left over after tree felling) favour New Zealand Falcons because they provide suitable cover for nesting as well as ideal habitat for the Falcons’ prey (Freedman et al. 1996). Although there was no opportunity to test this, alternative land management practices, such as burning or removing pine slash, may make sites less suitable for Falcon nesting. Burning or removing pine slash would remove potential nest-cover, may reduce prey abundance (Hartley 2002), and the ash left after burning may not provide a suitable substrate for Falcon nests. This could explain in part why attempts, the male of the pair changed between seasons and in 8% the female changed (n = 48). In no case was a pair holding a territory replaced by a completely new pair the following breeding season.

**Discussion**

**Breeding densities**

We suggest that the high densities of New Zealand Falcons in the plantation pines of Kaingaroa Forest are primarily the result of high abundance and availability of prey within this habitat (Seaton et al. 2008). Prey abundance is promoted by the highly heterogeneous landscape of differently aged stands, whereas availability of prey is high as a result of the abundant edge habitat, created by clear-felling fairly small, discrete, blocks of forest.

![Image](image_url)  
**Fig. 4.** The distance to the nearest stand edge (a border of trees differing in height by at least 4 m) of the nests located in 2004–05 and 2005–06 (n = 63) breeding seasons and randomly selected sites (n = 49).

<table>
<thead>
<tr>
<th>Age of pine compartment (year t)</th>
<th>Age of pine compartment (year t + 1)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>19</td>
<td>25</td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 4. Proportional use of forest compartments (%) by New Zealand Falcons during breeding seasons from 2003 to 2005 (n = 48)

Randomly selected site

Attempts, the male of the pair changed between seasons and in 8% the female changed (n = 48). In no case was a pair holding a territory replaced by a completely new pair the following breeding season.
New Zealand Falcons were not recorded breeding in pine forests historically, as previously it was common practice to burn pine slash before tree planting (Roberts 1994).

The recent colonisation of pine forests by New Zealand Falcons may also be linked to the large-scale use of 1080 poison for plantation pest control. Such baits have only been applied aerially over large areas since 1994 (Thomas and Taylor 2002). Pest control, as well as controlling plantation pests, is effective in controlling several introduced predators (Alterio 2000) that can have a negative impact on survival of Falcons, including mus-telids, feral Cats and Brushtail Possums (Fox 1977; Seaton et al. 2009). Control of these predators may be more beneficial to Falcons inhabiting pine forests than in more traditional habitats where they nest off the ground and are less susceptible to such predation (Fox 1977; Lawrence and Gay 1991; Barea 1995). This may explain the preferential selection of nest-sites in trees where indigenous forest bordered pine forest, but may also be linked to conservatism in choice of nesting site (Newton 1979). Control programs that are more specifically targeted at predators of Falcons, rather than just plantation pests, should benefit New Zealand Falcons even more. Nevertheless, caution should be maintained when using other forms of poison, especially those that are known to biologically accumulate (Stephenson et al. 1999).

Breeding dispersal

New Zealand Falcons showed strong pair-bonds between breeding seasons, a trait in common with other species of raptor (Newton 1979). Remaining with the same mate and in the same territory may make it easier for both members of a pair, because they are familiar with each other’s behaviour and the home range within which they breed (Warkentin et al. 1991). Despite these advantages of remaining in the same forestry compartment, New Zealand Falcons will need to assess the relative benefits of moving to compartments with younger trees. In pine plantations, the average breeding dispersal of Falcons was ~0.9 km, which falls well within the average home range radius of ~1.7 km (Seaton 2007). Falcons preferred nesting in very young stands, and they tended to remain within the same stand or move to a younger stand in subsequent breeding seasons. Thus, it seems likely that if a younger stand is created between breeding seasons, Falcon pairs will move to breed in this stand. If not, they are more likely to breed in the same stand for another season.

Management recommendations

Populations of New Zealand Falcons benefit from clear-fell harvesting that creates a mosaic of stand ages across a plantation. This practice provides both suitable nesting sites and an abundance of available prey (Seaton et al. 2008). If plantations have trees of the same age, they will lack the edge habitat necessary for both hunting and suitable nesting sites.

Forestry managers can support populations of New Zealand Falcons by:

1. Maximising the temporal and spatial availability of stands <4 years old bordering stands >20 years old, thus maintaining a high local heterogeneity of stand ages throughout a plantation.

2. Leaving pine slash after harvesting operations to provide nesting cover and foraging opportunities for Falcons and their prey.

3. Employing predator control techniques that target predators of New Zealand Falcons.

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