GEOGRAPHIC ANALYSIS OF NATURAL FIRE ROTATION IN THE CALIFORNIA REDWOOD FOREST DURING THE SUPPRESSION ERA

Christopher B. Oneal[1], John D. Stuart[2], Steven J. Steinberg[3], and Lawrence Fox III[2]

[1]Center for Applied Geographic Information Science
Department of Geography and Earth Sciences, University of North Carolina at Charlotte
9201 University City Boulevard Charlotte, North Carolina 28223

[2]Department of Forestry and Watershed Management, Humboldt State University,
1 Harpst Street Arcata, CA., 95521

[3]Department of Environmental and Natural Resource Sciences, Humboldt State University,
1 Harpst Street Arcata, CA., 95521

ABSTRACT

A geographic information system (GIS) was used to analyze the effects of six physical variables (redwood sub-region, slope, aspect, elevation, distance from the coast, and moisture regime) on the natural fire rotation (NFR) of redwood (*Sequoia sempervirens*) forests between 1950 and 2003. NFR is defined as the years necessary for fires to burn over an area equal to that of the study area. This analysis relied on a spatial database of forest fire locations cataloged by California Department of Forestry and Fire Protection. The NFR for the California range of redwood forests was calculated as 778 years. The NFRs for north, central, and southern redwood sub-regions were 1,083, 717, and 551 years, respectively. The NFR of slope classes varied between 3,309 years for flat terrain and 423 years for steep slopes. The NFRs of north and south aspects were 796 years and 763 years, respectively. Elevation classes of 200 m illustrated a consistent decreasing trend in NFR values, 1,841 in the lowest elevation class and 53 years in the highest. Distance from the coast was classed in 5 km increments up to 50 km with NFR values of 648 years in the 5 km class and 1,148 years in the 50 km class. The NFRs of moisture regime classes were 1,183 years in the wettest class and 117 years for the driest class. Drier moisture regime classes were prevalent in the southern redwood range. The NFR calculated for redwood sub-regions, moisture regimes and elevation classes indicated that periodicity of fire in redwood stands decreased along a north-south, west-east gradient. The NFRs observed in these redwood variables substantiate results from previous work concerning the influence of a north-south, ocean-inland gradient on fire frequency in redwood forests.

INTRODUCTION

The time period for this study was encompassed within the suppression era. It is recognized that anthropogenic factors were influential on results reported here; hence the term "natural" fire rotation should not be interpreted in the strictest sense. In this study, utilization of the term natural fire rotation is in keeping with its conventional use as a fire frequency metric.

Characterization of contemporary fire regimes at a landscape level necessitates the use of Geographic Information Systems (GIS) and requires the development of spatial data at an appropriate scale for investigating departure from historic fire regimes (Schmidt et al. 2002)

The mean fire interval (MFI), which is a common descriptor used to define fire frequency, has limited applications when calculated over large geographic extents. As a study area increases beyond a certain size, the MFI ceases to be an appropriate measure of frequency (Agee 1990) because of its inverse relationship to the sample unit size (Arno and Petersen 1983). In large landscapes consideration of the proportion of the area burned when calculating fire frequency may comparatively yield a more representative measure than that of a point frequency. For the 215, 000 ha area comprising the Boundary Waters Canoe area in Minnesota, the natural fire rotation (NFR) was developed as a measure of fire frequency (Heinselman 1973). A similarly large area, the 880,000 ha of California's redwood (*Sequoia sempervirens*) forests (Fox and Lee 1989) warrant the use of NFR as a measure of fire periodicity.

Previous studies have described the historic fire regime of redwood forests (Fritz 1931; Veirs 1982; Finney and Martin 1992; Stephens and Fry 2005). Delineation of time periods for which periodicity of fires is defined is generally grouped into pre-Euro-American settlement, settlement, and suppression eras, though exact dates of these vary regionally. Within redwood forests, descriptions of the modern fire suppression era are defined here as 1950 to 2003. Fire suppression existed in redwood forests before 1950 however, fire prevention laws were not applicable to the redwood belt until 1945 (Reynolds 1950). With the exception of one study covering the period 1929-1979 (Greenlee and Langenheim 1990), no other published descriptions of contemporary redwood fire regimes were found. Issues of scale and environmental setting hinder meaningful comparisons between fire history studies in redwood. Composite and area frequencies of fire periodicity are dependent on the area over which they are calculated (Kilgore and Taylor 1979; Agee 1990; Arno and Petersen 1983). Comparisons of study results have often been made between sites that vary greatly in size and environmental setting. For example, Veirs (1980) studied the fire history of redwood in its northern extent on 1 ha plots while Greenlee and Langenheim (1990) described the fire regime of redwood for an area of 115,000 ha in its southern extent.

Topography, stand structure, and forest associates, which vary throughout the range of redwood, are recognized by ecologists as factors that may help explain differences in fire frequencies (Jacobs, Cole, and McBride 1985). Variations in fire return intervals as they relate to slope position (Greenlee 1983), slope steepness (Brown and Baxter 2003), latitude (Greenlee 1983; Finney and Martin 1989), distance from the coast (Veirs 1980; Brown and Baxter 2003), elevation (Veirs 1980, 1982), and aspect (Stuart 1987; Stephens and Fry 2005) have been discussed. However, the fire regime of redwood has not been quantified on the basis of such physical parameters, derived from a GIS.

Fuel moisture has been recognized as an important factor in occurrence and severity of wildland fires (Mutch 1970). Slope and aspect play an integral part in determining the potential fuel moisture that governs fire behavior. Southerly aspects receive higher solar insolation and evaporation thus reducing fuel moisture, while steeper slopes allow fires to spread faster (Rothermel and Anderson 1966; Agee 1993). In redwood forests, distance from the coast influences relative humidity, fog occurrence (Stuart and Stephens in press), and fire periodicity (Veirs 1980). Higher elevations, which occur further from the coast, are subjected to fluxes in temperature (Zinke 1988), affecting the length of the fire season (Agee 1993; Stuart and Stephens in press). The moist, fog-laden, coastal maritime climate of the redwood region varies spatially from north to south and with increasing distance from the coast (Sawyer et al. 2000a; Zinke 1988; Stuart and Stephens in press). Differences reported in fire frequencies throughout the range of redwood are attributed in part to this latitudinal, ocean-inland moisture gradient (Stuart 1987; Veirs 1982; Greenlee 1983). While some studies include topography and moisture regime as a descriptor of site location (Stuart 1987; Veirs 1982; Brown and Baxter 2003), the influence of these parameters as they relate to fire frequency is unclear. In this study, a GIS was used to explore spatial relationships of topography, moisture gradient, distance from the coast, and geographic sub-regions, as related to fire periodicity of the modern suppression era within California's redwood forests.

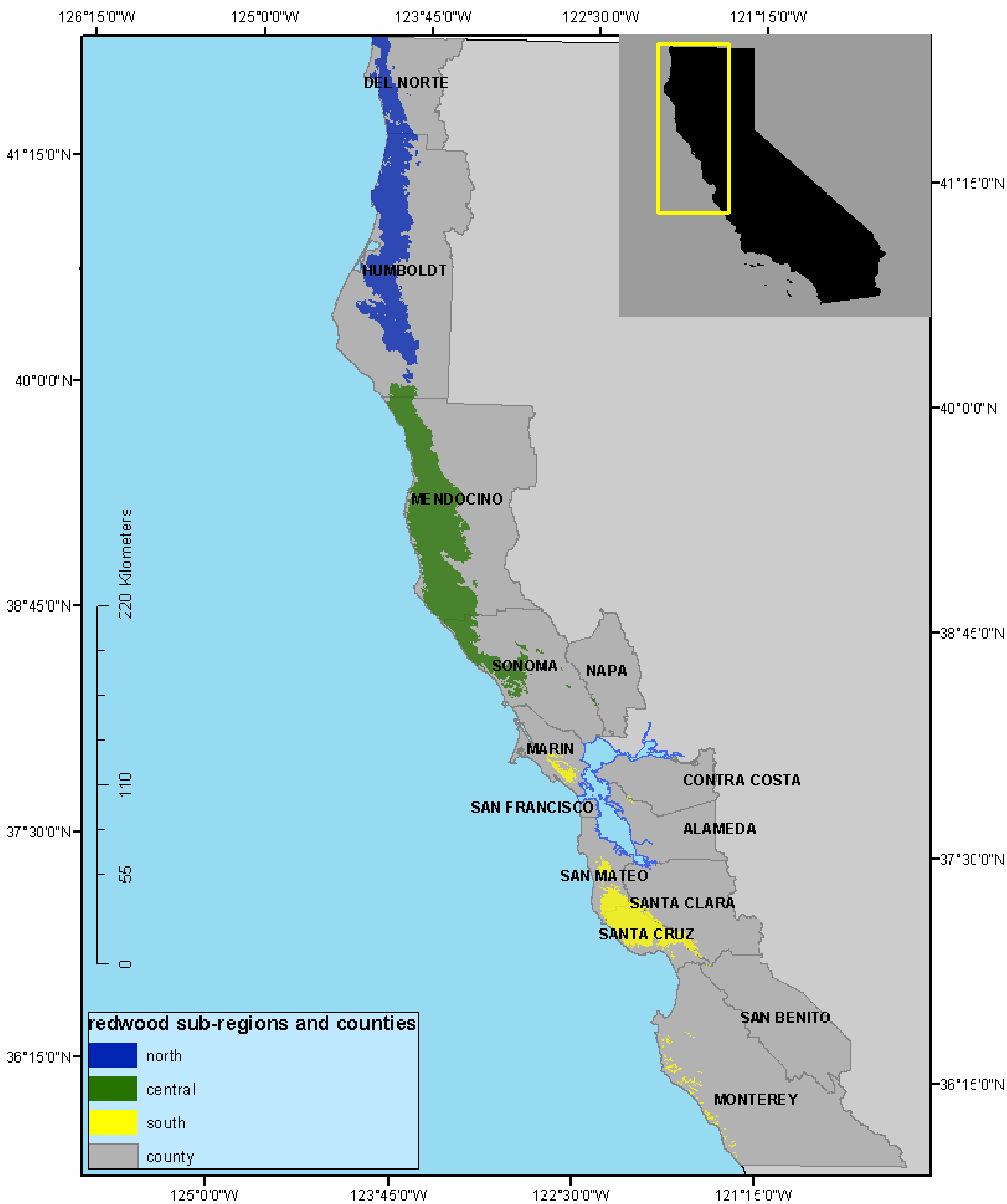
METHODS

Study Area

The range of redwood in California (Figure 1) is confined to a noncontiguous narrow belt, 10 to 50 km wide (Roy 1966), ranging in latitude from the northern state border to 35º 49′ N in the South. The range includes an area of approximately 880,000 ha, stretching 724 km along the California coast (Sawyer et al. 2000b; Fox and Lee 1989). Isolated stands may be found in the extreme eastern sections of Del Norte and Napa County, and straddling the Alameda and Contra Costa Counties border (Fox and Lee 1989). The most southerly stands of redwood inhabit coastal Monterey County. Within its range, redwood may be found on progressively higher elevation sites in more southerly locations.

California has a Mediterranean climate with a summer drought period that governs the fire season, which begins in July and tapers off with the arrival of the wet season in November. Mean annual temperatures within coastal redwood fluctuate between 10º C and 15.5º C (Roy 1966). Inland locations experience more temperature extremes than along the coast. Average precipitation based on 1971-2000 normals (Daly 2004) for the entire range of redwood vary between 460 mm in the southern extent and 2400 mm in the northern extent. In the northern extent of redwood, fog contributes considerably to annual water input during the summer months. Fog drip has been recorded as high as 425 mm in Humboldt County, with fog extending as far as 42 km inland (Roy 1966; Byers 1953; Azevedo and Morgan 1974). Fog may account for as much as 34 percent of total water input in the northern extent of redwood (Dawson 1998). However, fog is not as prevalent in the southern extent of redwood (Byers 1953). Although occurrence varies spatially and temporally, there is a general decrease in the amount of fog drip with increasing distance from the coast (Azevedo and Morgan 1974). Coast redwood forests are composed of north, central, and southern sub-regions as dictated by moisture regime (Sawyer et al. 2000a).

Figure 1. Geographic extent of the three primary sub-regions of redwood within California counties.



Redwood Sub-regions

The northern redwood sub-region is distributed from 124º 14′ W, 42º 00′ N in Del Norte County, to 123º 50′ W, 40º 4′ N in Humboldt County (Figure 1), ending at a natural break in redwood distribution, 10 km north of the Mendocino County line. This sub-region contains approximately 325,000 ha of redwood forests (Fox and Lee 1989), ranging in elevation between 2 and 820 m. Average annual precipitation and temperature normals from 1971-2000 (Daly 2004) for this sub-region are between 1,100 mm to 2,400 mm, and 10º C to 13º C, respectively. The *Sequoia sempervirens-Pseudotsuga menziesii/Rhododendron macrophyllum* association (Figure 2) is representative of one of the six associations that may be found in redwood forests within this redwood sub-region (Mahony and Stuart 2001).

The extent of central redwood defined here is bound between 123º 58′ W, 40º 4′ N, and 122º 23′ W, 38º 19′ N (Figure 1). The majority of the central redwood sub-region is contained within southern Humboldt and Mendocino Counties. In Sonoma County, the distribution becomes disjointed, and its easternmost border approaches Napa County. Average annual precipitation and temperature range between 950 mm and 2,250 mm, and 11º C to 15º C, respectively (Daly 2004). Elevation of redwood forests in the central sub-region ranges from 17 m to 717 m. The 400,000 ha of redwood forests of this region (Fox and Lee 1989) are ecologically and compositionally less like the northern range (Sawyer et al. 2000b). Central redwood forests (Figure 3) are more closely associated with the surrounding Douglas-fir (*Pseudotsuga menziesii*)-hardwood forests than the more northern forests (Zinke 1988).

The 135,000 ha of redwood in the southern sub-region (Fox and Lee 1989) is patchier in its distribution than either the northern or central sub-regions. Redwood extends from 122º 44′ W, 38º 4′ N in Marin County to as far south as 121º 22′ W, 35º 49′ N in Monterey County. Distribution of redwood in this area is strongly affected by available moisture. Redwoods in this sub-region are most often located within 55 m of a stream channel (Borchert, Segotta, and Purser 1988; Zinke 1988). Precipitation ranges from 460 mm and 1,300 mm, with an average temperature range similar to the central sub-region (Daly 2004). Redwood can be found on moist sites in this area that range in elevation from 46 m to 1,400 m. The coastline is characterized by hilly scrub and is incised by deep ravines that constitute relatively short stream courses (Sawyer et al. 2000b; Borchert, Segotta, and Purser 1988). In its southern extent, redwood transitions abruptly into coastal scrub and chaparral (Borchert, Segotta, and Purser 1988) (Figure 4).

GIS model

Polygon data sets acquired for analysis in this study consisted of redwood vegetation and fire perimeter data layers for California and were obtained from California Department of Forestry and Fire Protection's (CDF) Fire and Resource Assessment Program (FRAP 2003). Grid data sets used for analysis were derived from a digital elevation model (DEM) and a climatic spatial data source. The redwood data layer (Figure 1), was mapped at 1:130,000 scale from 1986 air photos (Fox and Lee 1989). The map represents the range in which redwood can naturally grow and reproduce within California and does not imply that redwood is dominant at every location on the map.

The CDF provided fire perimeter data at a map scale of 1:24,000. Two criteria were established for fires to be included in this study: the fire must have occurred within the time frame under consideration (1950-2003),

Figure 2. The *Sequoia sempervirens-Pseudotsuga menziesii/Rhododendron macrophyllum* association is a representative forest type found in the northern redwood sub-region. This stand is located in Del Norte Redwoods State Park along the Damnation Creek Trail in Del Norte County, CA.

and it must have been "large", as defined by public agencies as 121 ha or greater. All of the large fires (> 121 ha) in redwood recorded by the California Department of Forestry and Fire Protection between 1950 and 2003 were included in this study. Fire data were not sampled, as the data set was a census. Comprehensive geo-data sets are unlike data obtained from sample surveys, which require specific sampling procedures and statistical analyses. Because data included in analysis make up the known population of large fires in redwood between 1950 and 2003, no statistical inference to that population was warranted.

The GIS was used to query areas within the spatial and temporal bounds specified by the user. The GIS model constructed in this study consisted of the following parameters: fire, redwood, elevation, slope, aspect, redwood sub-region, distance from the coast, and moisture regime (Budyko Index). It is from this model that all area queries were performed. Acquiring values for the NFR equation (equation 1) was accomplished using two queries: 1) total area of each parameter and 2) area burned in each parameter. The third factor in the NFR equation, time, was declared within the query statement bounding the time period for which areas burned were queried. Query results were used to calculate NFR within a flat database file.

Equation 1. NFR equation

$$\text{NFR} = \frac{\Delta\text{years}}{\left(\frac{\sum \text{A}_{\text{burned}}}{\text{A}_{\text{total}}}\right)} \quad (1)$$

where:

Δyears = the time period for which NFR is calculated

$\sum \text{A}_{\text{burned}}$ = summation of area burned within the time period

A_{total} = the total area over which NFR is calculated

$$\text{Budyko index} = \sum_{i=1}^{12}\left(\frac{\text{PET}_i}{\text{Precip}_i}\right) \quad (2)$$

where:

Precip = total monthly precipitation (mm)

$$\text{PET} = 924 \times \text{Daylength}_{\text{month}} \times 0.611\,\hat{}\left(\frac{\left(\frac{17.3 \times \text{Daylength}_{\text{month}}}{\text{Temp}_{\text{month}} + 237.3}\right)}{\text{Temp}_{\text{month}} + 273.2}\right) \quad (3)$$

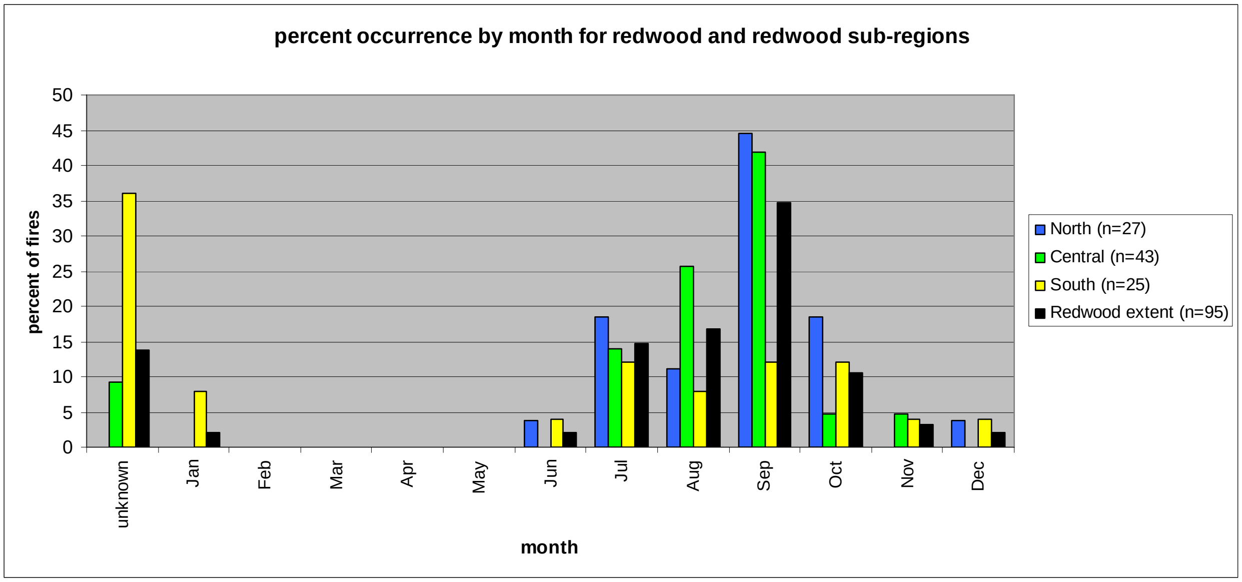
where:

$\text{Daylength}_{\text{month}}$ = hours daylight by month

Figure 3. The redwood-Douglas-fir/hardwood association is a representative forest type found in the central redwood sub-region. This stand is situated in Montgomery Redwoods State Reserve located in Mendocino County, CA.

Figure 4. Redwood stands of the southern redwood sub-region are generally confined to drainages flanked by coastal scrub and chaparral as shown in these stands located in Big Sur, Monterey County, CA.

Figure 5. Percent occurrence of fires by month for the range of redwood, and redwood sub-regions. Data were tabulated for large fires in redwood for the time period (1950-2003) and consisted of 95 fires within its range. The number of fire events in the north, central, and southern redwood sub-regions were 27, 43, and 25, respectively.



Elevation data were obtained from the EROS data center as a 30 m^2 resolution, seamless DEM mosaic covering the study area (USGS 2003). The DEM was classified into 14, 200-m increment classes. Slope and aspect were constructed from the DEM using the ArcGIS 8.3 Spatial Analyst extension. Slope classes were defined by percentages where: less than 10 percent slope was defined as "flat", 10 to 29 percent as "gentle", 29 to 49 percent as "moderate", and greater than 49 percent as "steep". Aspect was classified into north: 0 to 90 degrees and 270 to 360 degrees, and south: 90 to 270 degrees. Redwood sub-regions were delineated according to guidelines established by Sawyer et al. (2000a) and followed natural breaks in redwood continuity. Distance from the coast was established by buffering the California coastline into 5-km increments to create 10 classes, up to 50 km from the coast.

Jacobs et al. (1985) noted problems arising from generalization of fire frequency without accounting for spatial variation in temperature and precipitation. In an effort to avoid these inherent problems in this analysis, a spatial climatological ratio grid of annual potential evapotranspiration (PET) to annual precipitation (equation 2), termed a Budyko index (Zinke 1988; Budyko 1974), was constructed. This grid was used as a parameter to represent moisture regime. The Budyko index is a robust estimator of the moisture regime in redwood because it incorporates both temperature and precipitation into its calculation.

Potential evapotranspiration (PET) has been proven useful as an index of the "drying power" of ambient meteorological conditions (Dingman 2001). A temperature based, 1971-2000 normals PET grid was constructed using an equation created by Hamon (1963, equation 3). Spatial precipitation and temperature data were obtained from the Spatial Climate Analysis Service as ASCII text files and were converted to grids. The GIS product was a summation of monthly PET values as one 30 m^2 spatial grid.

Table 1. Natural fire rotation (NFR) for redwood sub-regions. NFR is reported in years. Percentage of sub-region burned is the percentage of total area burned in each redwood sub-region between 1950 and 2003.

	redwood sub-regions			redwood region
	north	central	south	
hectares burned	15,893	30,911	12,936	59,740
# fires	25	43	27	95
% sub-region burned	5	7	10	7
% sub-region re-burned	0.4	1.3	9.3	2.2
NFR	1,083	717	551	778

The climatic spatial data sets used in this study were created by a Parameter Elevation Regression on Independent Slopes Model (PRISM) (Daly 2004). Using a dynamic search radius for input weather stations PRISM computes spatial data sets by incorporating into calculation adiabatic lapse rates, orrographic effects, coastal proximity and other environmental factors.

RESULTS

Occurrences of large fires (> 121 ha) in redwood forests between January and June peaked in September, accounting for 35 percent of all fires for the time period of the study (Figure 5). Fourteen percent of all fires in the range of redwood had no month documented. Analysis by sub-region showed that the highest percentage of fires occurred in September for all but the southern sub-region in which 36 percent were of an unknown month (Figure 5). However, the months of July, September, and October shared the next highest percentage of fire occurrences at 12 percent within the southern sub-region. The southern sub-region was the only sub-region that had fires in January.

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The central redwood sub-region experienced the most fires, 43, while the southern sub-region had the least, 25 (Table 1). The distribution of fires in the north (Figure 6) and central sub-regions (Figure 7) showed no visually distinguishable spatial pattern of occurrence. Of the 27 fires in the southern sub-region (Figure 8), 70 percent occurred in the “stringers” of redwood in the southern extremity of this sub-region (Figure 9). The cause of fires in redwood was poorly documented. Eighty percent were of unknown causes, 14 percent were classified as miscellaneous, while the remaining six percent were documented as lightning (three percent), arson (two percent) or equipment (one percent) fires. During the modern fire suppression era in redwood, 95 fires burned 59,740 ha, resulting in a NFR of 778 years. The NFR calculated for the sub-regions for the time period 1950-2003: north, central and south, were 1,083 years, 717 years, and 551 years, respectively (Table 1). The southern sub-region had the highest percentage of area re-burned at 9.3 percent, while the lowest percent area re-burned, 0.4 percent, was observed in the northern sub-region.

Figure 6. Spatial distribution of fires (1950-2003) in the northern redwood sub-region n=25. Identification of individual fires may be masked due to overlapping fires.

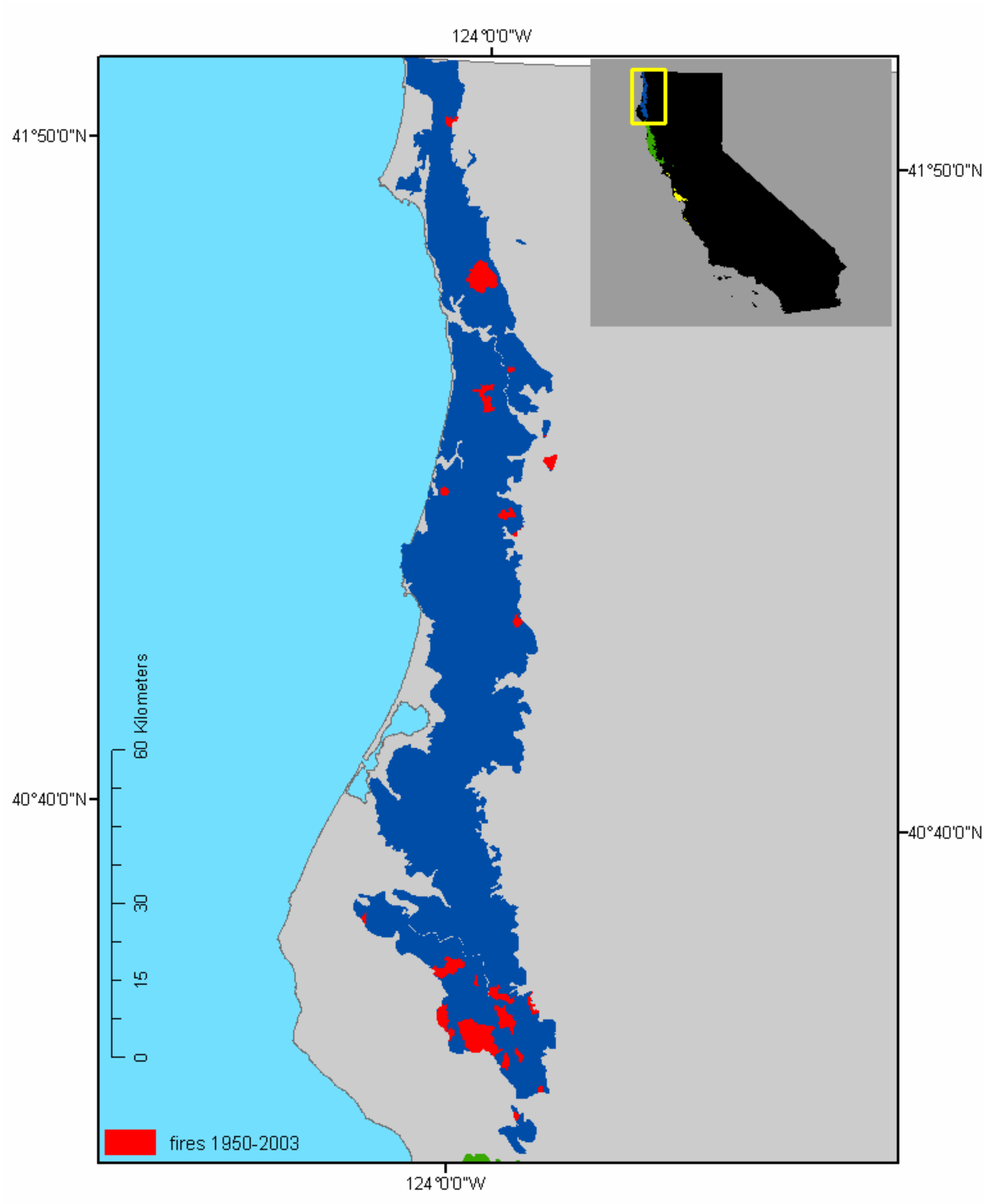


Figure 7. Spatial distribution of fires (1950-2003) in the central redwood sub-region n=43. Identification of individual fires may be masked due to overlapping fires.

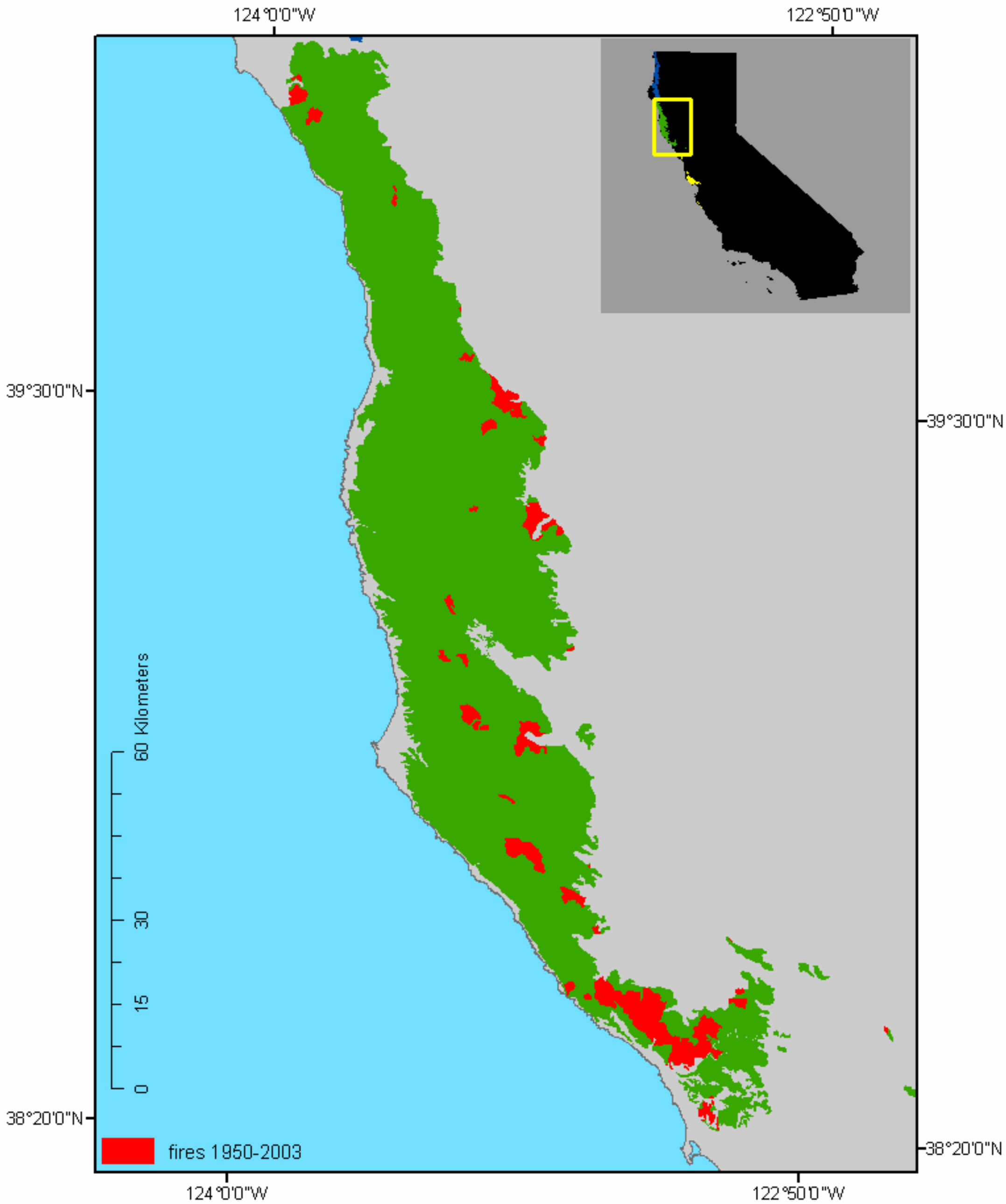


Figure 8. Spatial distribution of fires (1950-2003) in the southern redwood sub-region n=27. Identification of individual fires may be masked due to overlapping fires.

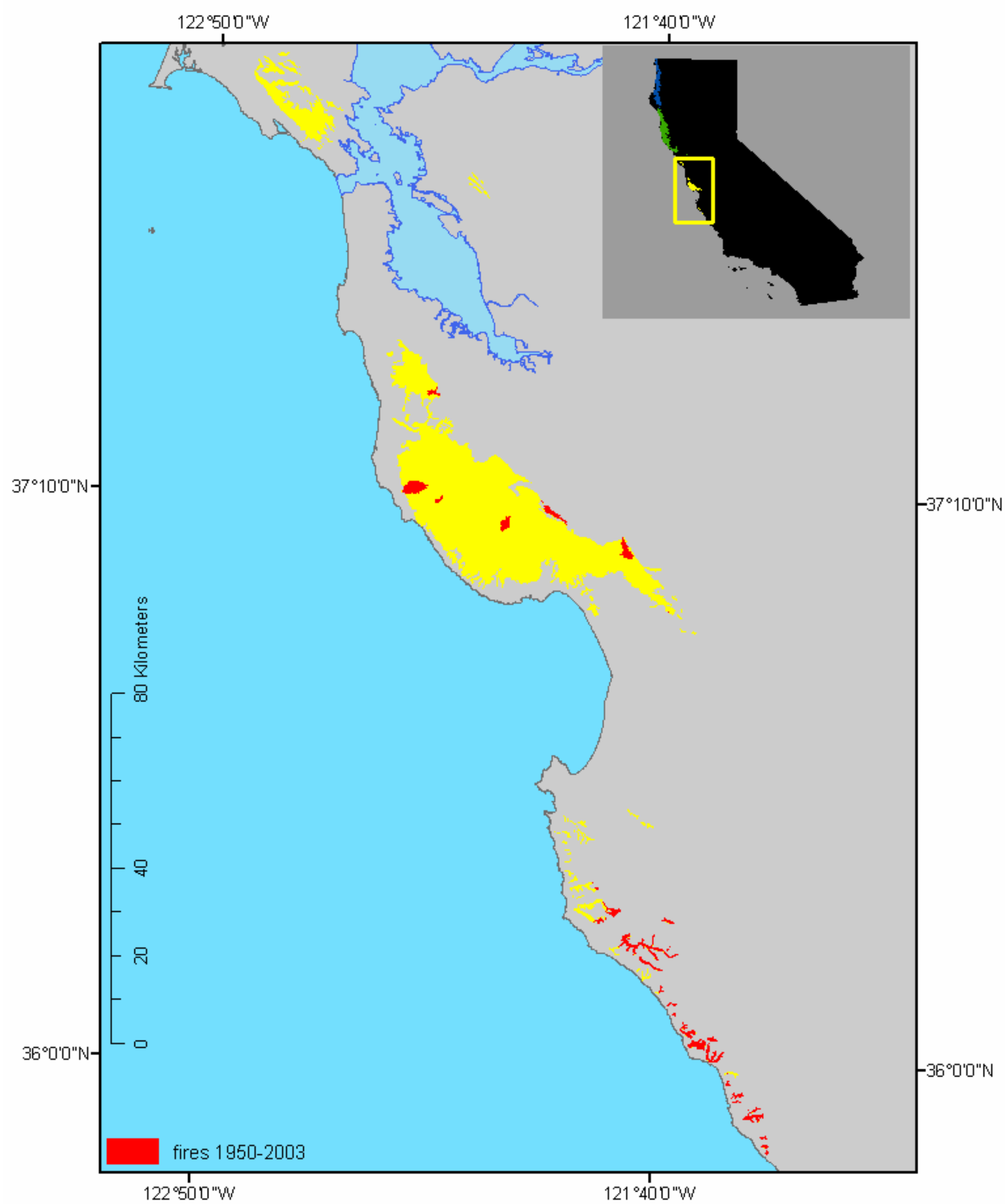


Figure 9. Spatial distribution of fires (1950-2003) in the southern extremity of the southern redwood sub-region. Identification of individual fires may be masked due to overlapping fires.

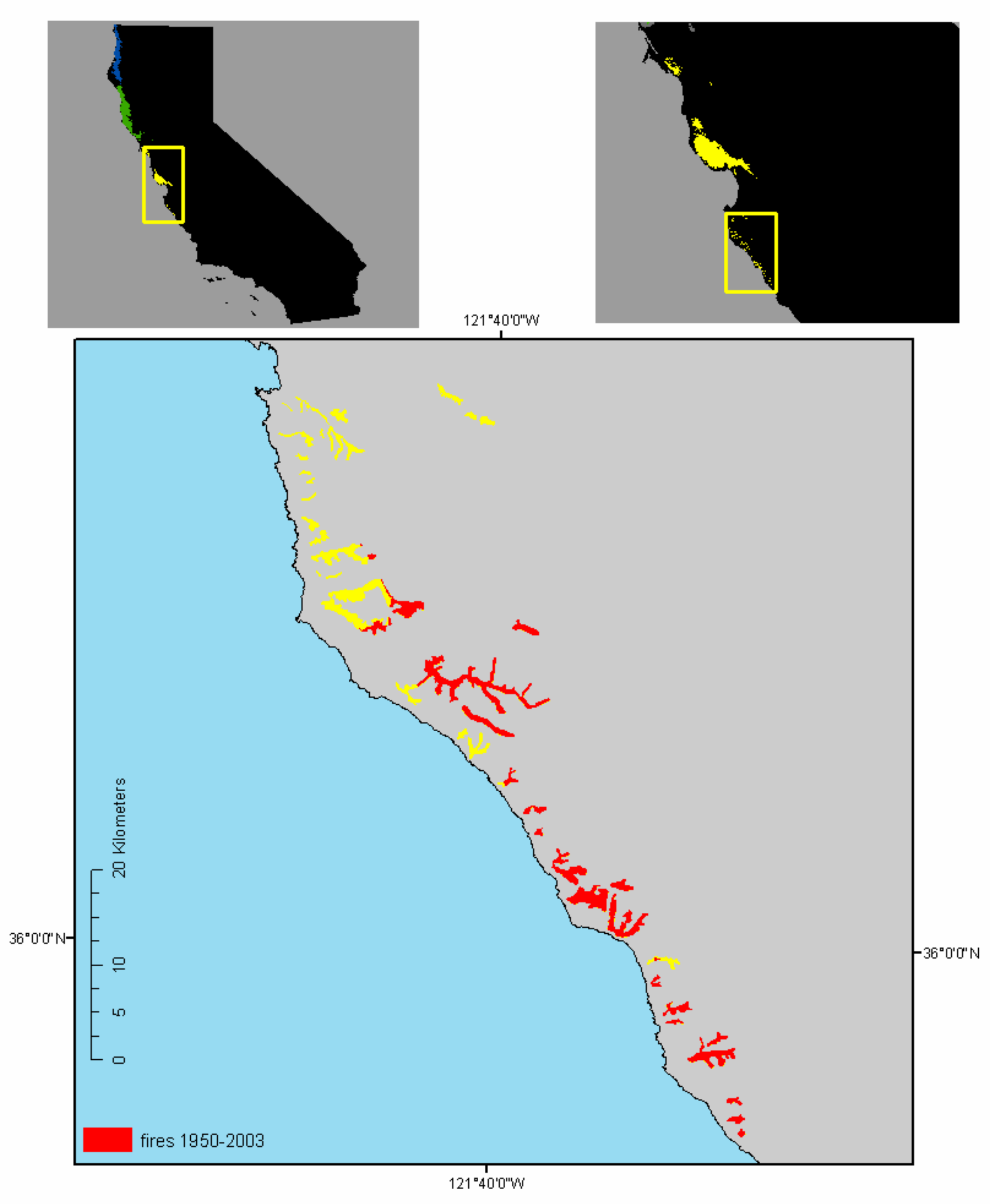


Table 2. NFR calculated for the range of redwood and redwood sub-regions by distance from the Pacific Coast in 5 kilometer distance classes. "NA" (not applicable) denotes classes in which redwood was not present.

distance classes	redwood range	redwood sub-regions		
(km)	(Years)	north (Years)	central (Years)	south (Years)
5	648	11,471	659	196
10	525	1,247	491	583
15	1,761	4,209	1,149	2,609
20	1,782	2,660	2,812	689
25	446	308	504	11,474
30	769	457	2,330	NA
35	324	393	230	NA
40	911	1,407	230	NA
45	470	NA	168	NA
50	1,180	NA	1,180	NA

The NFRs of north and south facing slope classes were 796 years and 763 years, respectively. Steeper slope classes had lower NFRs. The NFRs of slope classes were calculated in a wide range. "Flat" was determined to have an NFR of 3,309 years, "gentle" at 1,319 years, "moderate" at 800 years and "steep" at 423 years. The NFR of distance-from-the-coast classes for the extent of redwood ranged in value from 324 years in the 35-km class up to 1,782 years in the 20-km class (Table 2). When calculated by redwood sub-region, differences in NFR values for distance classes were as great as 10,000 years between two successive classes. This was observed in the southern sub-region. Elevation was inversely proportional to the NFR calculated for each 200-m class throughout the range of redwood and is illustrated here by redwood sub-region (Figures 10, 11, and 12).

Reductions in NFR were observed in "drier" Budyko index classes (Figures 13, 14, 15, and 16). The ten equal-interval classes calculated for Budyko index within redwood ranged from 0.28 mm in class 1, to 1.70 mm in class 10 (Table 3). Successively larger Budyko index values were indicative of greater moisture demand. Figures 13, 14, 15, and 16 illustrate a well-defined north to south moisture gradient throughout the range of redwood. Classes 1 through 4 dominated the northern extent of redwood while classes 5 through 10 occupied the more southerly extents.

Figure 10. Two-hundred meter elevation classes in the northern redwood sub-region. NFR values displayed are those calculated over the entire range of redwood.

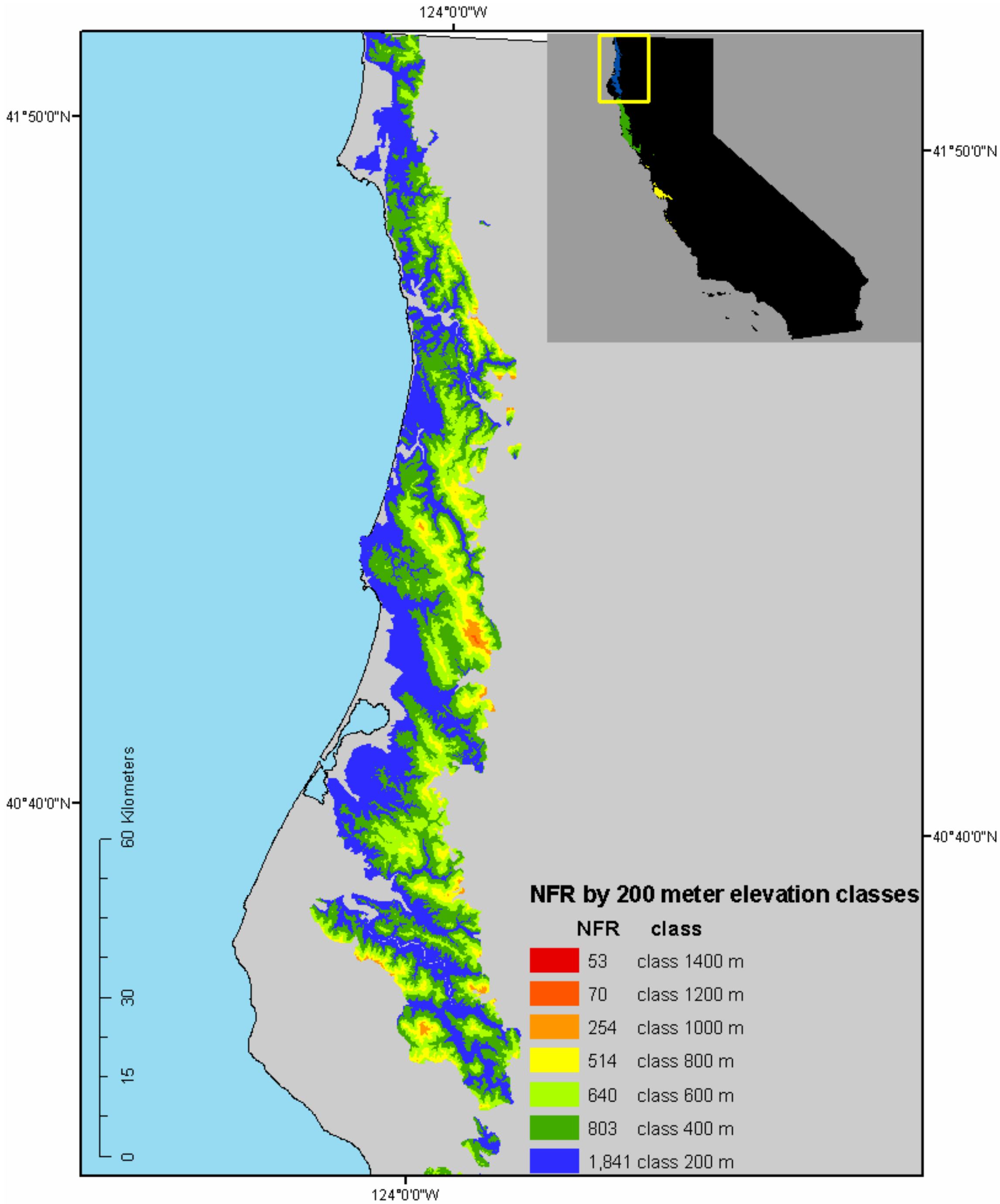


Figure 11. Two-hundred meter elevation classes in the central redwood sub-region. NFR values displayed are those calculated over the entire range of redwood.

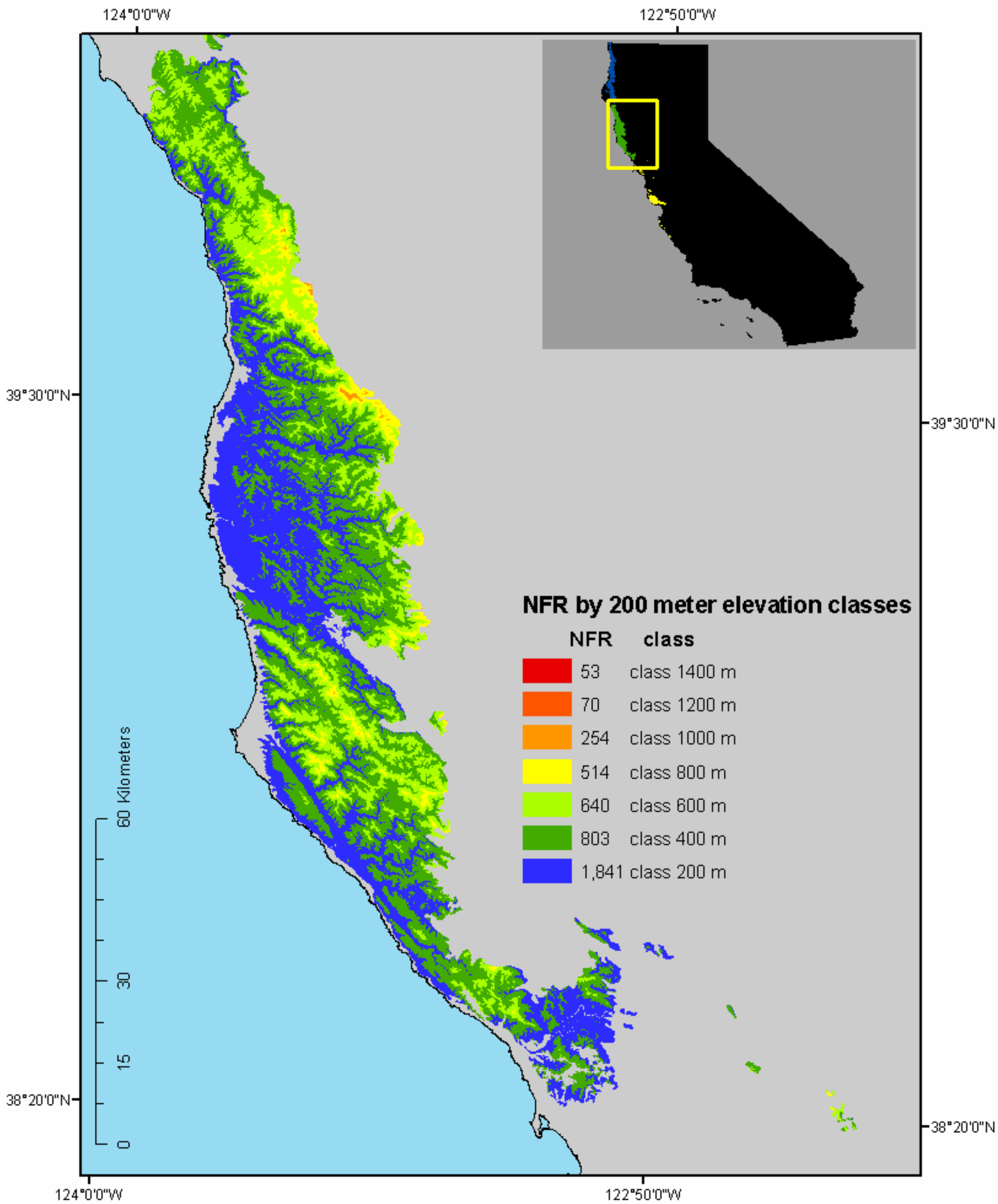


Figure 12. Two-hundred meter elevation classes in the southern redwood sub-region. NFR values displayed are those calculated over the entire range of redwood.

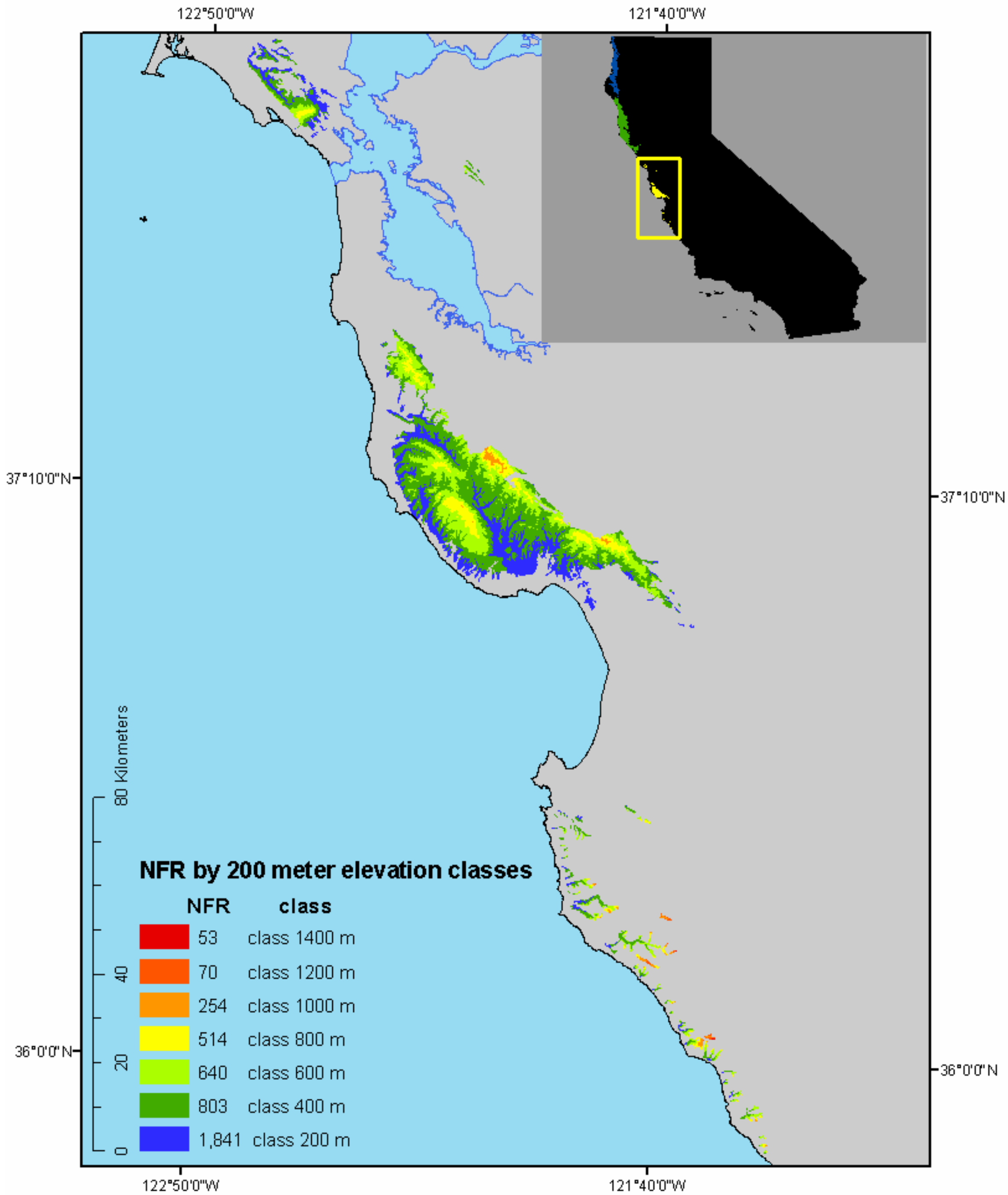


Table 3. Ten equal interval classes of Budyko index. Class value ranges, measured in millimeters, represent potential "moisture deficit" throughout the range of California redwood. Successively larger class values represent increasing potential "moisture deficit".

class	(mm)
1	0.28 - 0.42
2	0.43 - 0.57
3	0.58 - 0.71
4	0.72 - 0.89
5	0.85 - 0.99
6	1.00 - 1.13
7	1.14 - 1.27
8	1.28 - 1.41
9	1.42 - 1.55
10	1.56 - 1.70

DISCUSSION

The area calculations on which NFR is based make it sensitive to extremely disproportionate ratios of area burned to total area. Disproportionate area ratios may result in anomalous NFR values. In this study, aberrant NFR values were observed for areas less than 500 ha, or in areas where relatively small areas (or no area) burned. For example, the NFR calculated for Budyko index class 8, which comprises 401 ha of the range of California redwood, resulted in a value of 5,048 years (Figure 16). The NFR of Budyko index classes 9 (420 ha) and 10 (212 ha) were undefined, as no large fires burned in these areas during the 53 year period. The analyst may not always be able to control this phenomenon. It may be that relevant subdivisions of a study area simply result in small delineated areas, for which periodicity is calculated. It is imperative that disproportionate area ratios of the NFR calculation be considered when drawing conclusions from GIS analysis.

The NFR for slope and aspect classes were consistent with expected fire behavior for these topographic parameters. Steeper slopes equate to faster rates of fire spread, which result in greater area burned and a reduction in NFR (Rothermel and Anderson 1966). Furthermore, "flat" terrain (less than 10 percent slope) in redwood was generally observed in moist coastal sites and in riparian zones. This may have accounted for the 2,886-year difference in NFR between "flat" terrains and "steep" slopes (greater than 49 percent). The 33-year difference between north and south aspects may have been due to greater solar insolation and evaporation on southern exposures. However, the small differences in NFR indicate that aspect did not seem to be a major factor in periodicity of fire in redwood at a landscape level. This conclusion is consistent with that of Stephens and Fry (2005), who found no significant difference ($p < 0.05$) between mean fire intervals of aspects in redwood stands in the northeastern Santa Cruz Mountains.

The NFR calculated for 5-km distances from the coast was inconclusive in determining periodicity as related to an ocean-inland gradient (Table 2). Veirs (1982) attributed differences in

Figure 13. Equal interval classes of Budyko index in the northern redwood sub-region. NFR values displayed are those calculated over the entire range of redwood. Undefined denotes classes where no large fires burned during the time period of study.

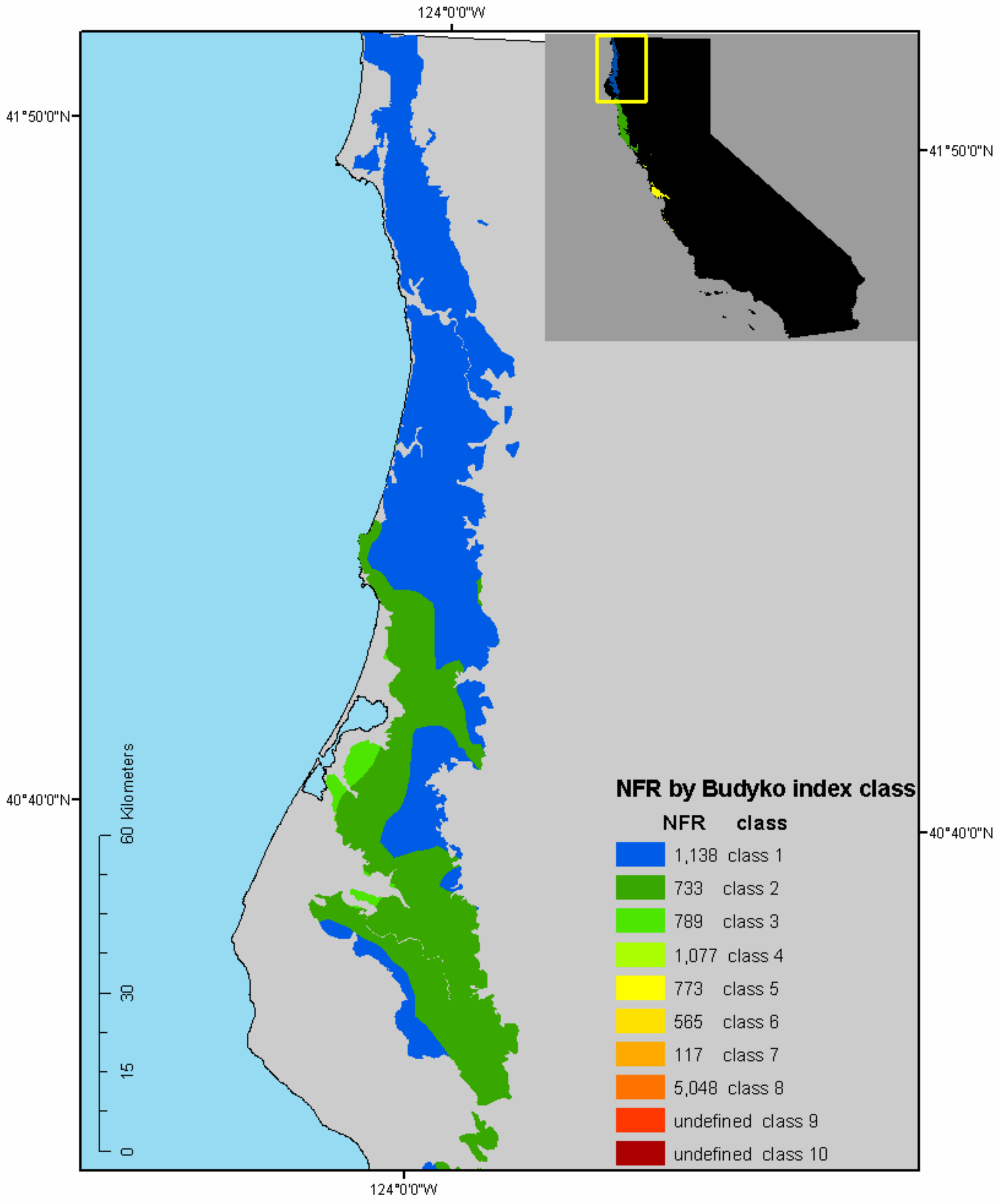


Figure 14. Equal interval classes of Budyko index in the central redwood sub-region. NFR values displayed are those calculated over the entire range of redwood. Undefined denotes classes where no large fires burned during the time period of study.

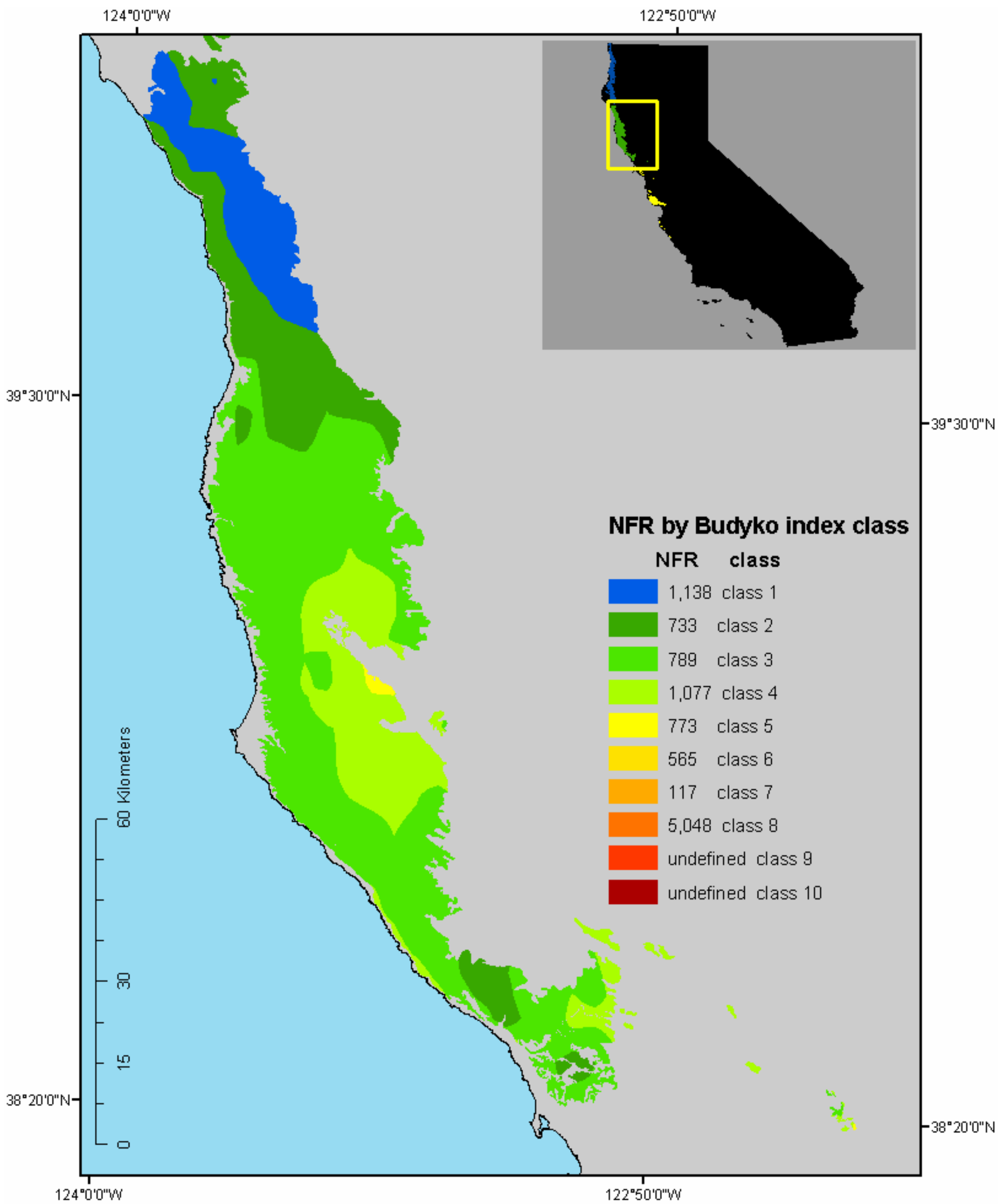


Figure 15. Equal interval classes of Budyko index in the southern redwood sub-region. NFR values displayed are those calculated over the entire range of redwood. Undefined denotes classes where no large fires burned during the time period of study.

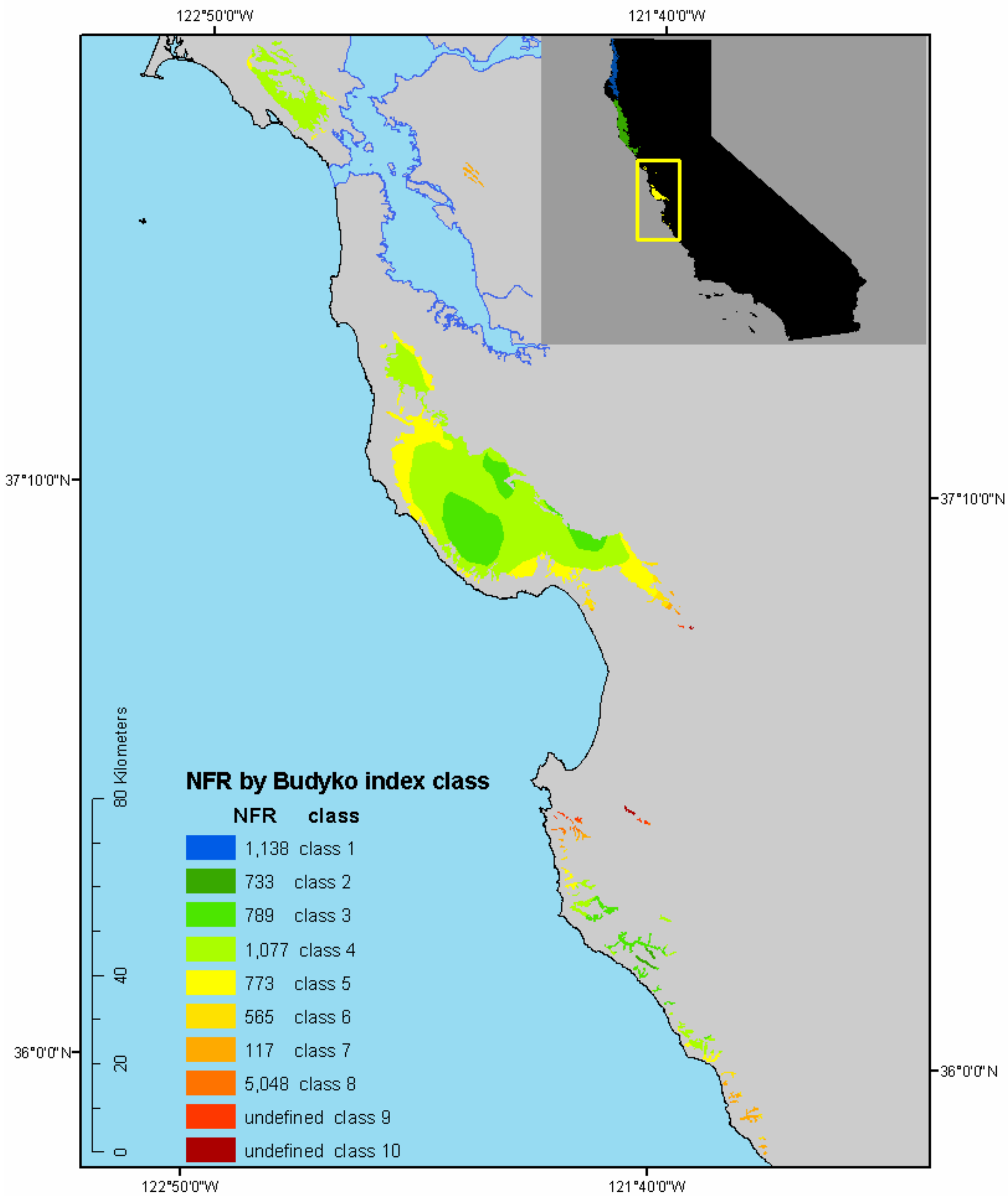
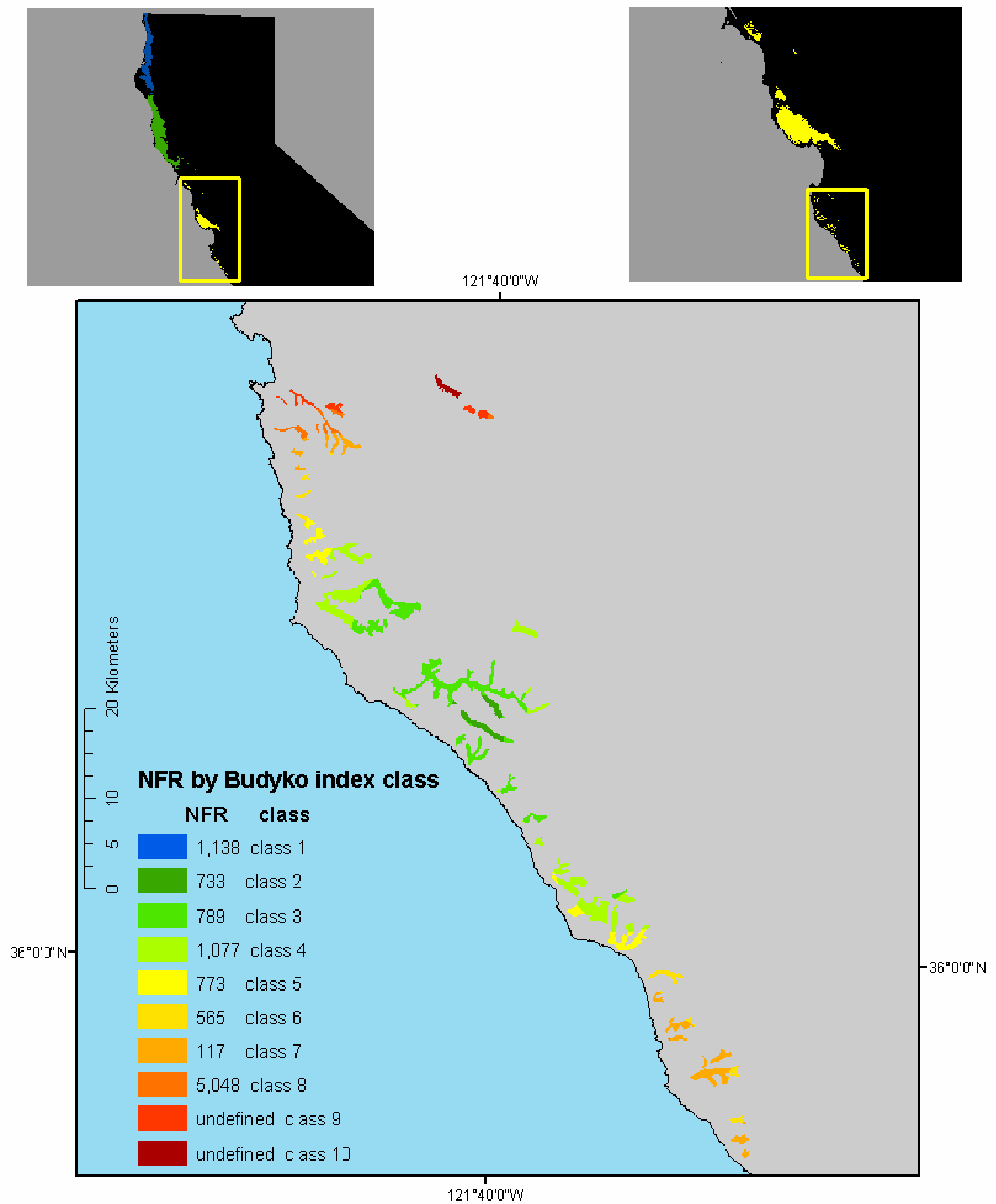


Figure 16. Equal interval classes of Budyko index in the southern extremity of the southern redwood sub-region. NFR values displayed are those calculated over the entire range of redwood. Undefined denotes classes where no large fires burned during the time period of study.



fire frequency between mesic low elevation sites (250-500 years) and xeric high elevation inland sites (50 years) to an ocean-inland gradient. Greater fog drip in stands closer to the coast was believed to be responsible for longer fire return intervals as compared to the shorter intervals of more inland stands (Jacobs, Cole, and McBride 1985). Brown and Baxter (2003) observed slightly decreasing intervals along an ocean-inland gradient in Mendocino County, located in the central redwood sub-region. This phenomenon was determined to be partly due to the number of trees included in the composite frequency, which was greater in more inland stands. In this study, no consistent trend was observed in NFR as calculated for successive distance classes.

It is important to note that in this study 5-km distance classes for which NFR was calculated were buffered exactly parallel to the Pacific Coast. The manner in which distance from the coast was defined may have masked the relationship of periodicity of fire to an ocean-inland gradient. The elevation gradient of the California coast progresses from northwest to southeast (Zinke 1988). Inspection of NFR by 200-m elevation classes of the range of redwood (Figures 10, 11, and 12) illustrates two points: fire rotation decreased with increasing elevation, and increases in elevation were observed at greater distances from the coast in a southeasterly direction. This finding reinforces the assertion of Veirs (1982) concerning the relation of an ocean-inland gradient to fire frequency in redwood.

The NFR calculated for each redwood sub-region indicated that latitude from north to south was influential in the fire frequency throughout redwood (Table 1). These reductions in NFR along a north-south gradient may be due to the spatial distribution of the fuel moisture regime of redwood as delineated by Budyko index classes. This distribution (Figures 13, 14, 15, and 16) shows that about 80 percent of the total area of the "wettest" Budyko index class (class 1) occurred in the northern sub-region (Figure 13). Budyko index class 1 was absent in the southern sub-region (Figures 15 and 16). Conversely, the "driest" Budyko index classes (classes 6-10) were altogether absent in the northern and central sub-regions (Figures 13 and 14). The moderating influence of moisture regime on fire periodicity in redwood is further evidenced by NFR values calculated for each Budyko class (Figures 13, 14, 15, and 16), which generally decreased with successively "drier" classes.

The NFRs calculated for successively higher Budyko index classes revealed a weakly supported decreasing trend in value. The NFR of Budyko classes 2 (733 years) and 3 (789 years) do not support the assertion of decreasing fire frequency with increased moisture stress. Consideration must be given to the fact that Budyko classes 1 through 4 dominated the more northerly range of redwood, which experienced heavy logging and more ignitions in the 1950s. With Humboldt County leading the way, the years following 1950 saw lumber production increase by three times that of any prior year, at over a billion board feet (Lydon 2001). It is likely that in the absence of logging activity, Budyko classes 1 through 4 would have had similarly longer NFRs. The increased moisture stress in the southerly redwood range is a probable explanation of depressed NFRs calculated in that sub-region.

The conclusion that NFR responded to a latitudinal climatic gradient is consistent with that of Greenlee (1983), who proposed that fire periodicity in redwood reflects north to south gradients in temperature and precipitation along the coast. This is further evidenced by NFR values of the recently posted fire rotation coverage for the state of California (FRAP 2003). At a much coarser scale, the fire rotation classes (>300 yr, 100-300 yr, and <100 yr) calculated for the same

53-year period illustrate decreases of NFR from north to south along the Pacific Coast. Stuart and Stephens (in press) have identified the interaction of west-east, north-south, and montane elevational gradients as partial determinants of vegetation patterns in northwestern California. The influence of these environmental gradients may also be a determinant of the fire regime in redwood; during the modern suppression era, the NFR decreased along west-east, north-south elevation and moisture gradients. Environmental conditions are acknowledged as sources of variation in previous plot based fire frequency studies (Veirs 1982; Finney and Martin 1989; Brown and Baxter 2003; Stuart 1987). Employment of a GIS to calculate NFR at a large scale offers a landscape perspective of the fire regime in redwood.

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