

Harvesting Chaparral Biomass for Energy—An Environmental Assessment¹

Philip J. Riggan and Paul H. Dunn²

Management techniques for chaparral are being developed to reduce the incidence and severity of wildfire, minimize the associated flooding and debris production, and enhance watershed resource values. One important technique is the periodic use of harvesting or prescribed fire to maintain a coarse mosaic of different-aged stands of chaparral. These mosaics break up large areas of heavy fuel accumulation and maintain a substantial area of chaparral in a young, productive state. The probability of large, intense wildfires and the accompanying adverse fire effects are reduced because fire spread is considerably retarded in young stands with their low dead fuel volume (Rothermel and Philpot 1973, Philpot 1974, Countryman 1974). Furthermore, harvesting in high productivity areas allows the use of energy accumulated in native fuels and could provide a locally important alternative source of energy.

CHAPARRAL BIOMASS

Considerable amounts of potential energy are present in the biomass of some chaparral communities. Biomass in mature *Adenostoma* - *Ceanothus* stands is as high as 50 MT/ha with average accumulation rates of 0.8 to 1.2 MT/ha-yr (table 1). Higher biomass accumulations are found in *Quercus dumosa* stands on north-facing slopes (fig. 1), where biomass as high as 100 MT/ha has been observed (Lisle Green, pers. commun.). Biomass in mature (age greater than 25 years), north-facing *Quercus*-dominated chaparral is commonly in the range of .45 to 60 MT/ha. If the biomass on the higher quality sites is harvested on a rotational basis, a substantial source of energy could result. With an energy content of 5 kcal/gm and biomass of .50 MT/ha, a 1-ha stand contains the energy equivalent of 182 barrels of oil (assuming 1.38×10^6 kcal/barrel [Zavitkovski 1979]). On this basis, 400 ha (1000 acres) of chaparral has

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²Soil Scientist and Microbiologist, respectively, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Glendora, Calif.

Abstract: Age-class management techniques for the California chaparral are being developed to reduce the incidence and impacts of severe wildfires. With periodic harvesting to maintain mosaics in high productivity areas, chaparral fuels may also provide a locally important source of wood energy. This paper presents estimates for biomass in chaparral; discusses the potential impacts of harvesting on stand productivity, composition, and nutrient relations; and suggests directions for future research.

a gross energy equivalent value of \$2 million (assuming \$30/barrel).

Chaparral harvesting is being considered as a management technique. Systems for the production of chaparral wood fuel products have been proposed, and a transportable wood densification unit is being developed under contract from the California Department of Forestry. This unit will be used for demonstrations using both chaparral biomass and industrial wood wastes to produce a compact product that is suitable as a charcoal substitute or an industrial fuel.

An engineering feasibility study has shown that the cost of harvesting and processing chaparral fuels using existing technology is prohibitive (Riley and others 1980). The market for chaparral fuel products is also limited because other wood wastes are more readily available and few industrial plants can use wood fuels (J. A. Miles, pers. commun.). However, alternative technologies have been proposed, including a mechanical harvester to cut and windrow the chaparral, a cable warden for collection (Miles and Moini 1980), and a compactor for producing a transportable product (Miles, pers. commun.), and these could improve the economics of harvesting. The energy costs of producing a fuel product from chaparral biomass are also favorable, since only 17 percent of the gross energy content is consumed during harvesting and initial processing (Riley and others 1980). If the economics of harvesting are improved and systems for using other wood fuels are developed, opportunities for using chaparral biomass may be realized.

Management of larger hardwood fuels, such as stands of *Quercus chrysolepis*, could also provide a highly desired source of firewood. Currently, the National forests are able to supply only a small fraction of the firewood demand in southern California. For example, the Mt. Baldy Ranger District, Angeles National Forest, receives about 3000 annual requests for wood permits and issues about 400, while commercial operators market oak firewood at \$150 to \$300 per cord. A harvesting system designed around such labor-intensive and less technological uses of wood energy could be feasible in southern California.

As research and demonstration of engineering and operational techniques for utilizing chaparral

Table 1--Biomass accumulations in mature chaparral stands

Location	Species ¹	Biomass	Biomass increment	Age (yrs)	References
		<u>MT/ha</u> ⁽²⁾	<u>MT/ha-yr</u> ⁽²⁾		
1. San Dimas Los Angeles Co.	a. Ccr	37 to 85	1.8 to 4.0	21	Weaver and Riggan, unpubl. data
	b. Af, Ccr	49	1.2	37	Specht 1969
2. Kitchen Creek, San Diego Co.	a. At, Cg	28	0.8	35	Riggan and Lopez 1981
	b. Qd	2.8	2.8	1	
	c. Qd	18.5	0.5	35	
3. Boulder Creek, San Diego Co.	Af, Cg	23	1.0	23	Mooney and others 1977
4. Santa Barbara Co.	Cm	63	2.7	21	Schlesinger and Gill 1980
5. Santa Barbara Co.	As, Af, Cc	30	1.2	25	Debano and Conrad 1978
6. Camp Pendleton, San Diego Co.	Qd	54			Chandler 1955
7. North Mtn. Exp. Area, Riverside Co.	Ar	72			Green 1970

¹Af--Adenostoma fasciculatum, Ar--Arctostaphylos spp., As--Adenostoma sparsifolium, Cc--Ceanothus cuneatus, Ccr--C. crassifolius, Cg--C. greggii, Cm--C. megacarpus, Qd--Quercus dumosa.

²Divide by 2.25 to obtain tons per acre.



Figure 1--Overview of biomass accumulation and cover in a 5-year-old mixed chaparral stand dominated by Quercus dumosa. The stand is located on a north-facing slope adjacent to the San Dimas Experimental Forest.

biomass continues, concurrent research must address the environmental implications of chaparral harvesting. Conceptually, two modes of harvesting may be envisioned with diverse environmental effects: harvesting with permanent fuel modification and a sustained yield, rotational harvest system in designated energy management areas.

HARVESTING FOR PERMANENT FUEL MODIFICATION

A number of serious resource problems can accompany permanent chaparral fuel modification or type conversion, and these should limit the use of harvesting for this purpose. Fuel type conversion of chaparral to grass can greatly increase rates of erosion and sediment yield, flooding, and watershed nutrient loss.

Erosion from converted areas on steep or unstable slopes can be high. At the San Dimas Experimental Forest, widespread soil slippage during the large storms of 1969 occurred in 16.7 percent of the area on converted hill slopes and 5.5 percent of comparable chaparral areas. Soil slippage was restricted to slopes greater than 60 percent (Rice and Foggin 1971). In the 354-ha

Monroe Canyon, where 17 ha of riparian zone vegetation were removed and 57 ha of hill slopes were converted to grass during 1958-60, flooding and debris production caused massive changes in stream channel geometry, removed eight times more material than from a comparable channel reach in a nearby chaparral watershed, and contributed a large portion of the 296,000 m³ of debris deposited in the Big Dalton reservoir (Orme and Bailey 1970).

The deep-seated roots of the chaparral contribute considerable stability to steep slopes. Conversion replaces these with a more dense but shallow grass root system, and the shear plane of soil slips often coincides with the lower reaches of this rooting zone. Removing chaparral for fuelbreaks similarly decreases slope stability. The resulting soil slips are a frequent feature of fuelbreaks above steep slopes in the San Gabriel Mountains.

A fuels management program in the National forests of southern California must deal with extensive areas of steep terrain. On the San Dimas Experimental Forest, for example, 86 percent of the hill slopes have a gradient exceeding 55 percent (Bentley 1961). Serious problems with erosion, debris production, and flooding could be expected if widespread type conversion were attempted.

Conversion of chaparral to grassland can lead to long-term changes in watershed nutrient loss because of inherent differences in the nutrient cycling properties of these communities. Type conversions to grass established in 1960 at Bell Canyon in the San Dimas Experimental Forest export eleven times more nitrate-nitrogen in streamwater than do comparable chaparral watersheds (Riggan and Lopez, in press). This could lead to a decline in primary production on the watershed and contribute to the existing nitrate pollution in streams and groundwater of the San Gabriel Valley.

Type conversions to grass, fuelbreaks, and areas of reduced stocking density in the chaparral are also subject to invasion by "flash-fuel" species such as the subshrubs, Eriogonum fasciculatum and Salvia mellifera (fig. 2). These species produce finely divided, compact fuels; rapidly accumulate dead material; and can establish relatively continuous fuel beds. The Salvia also contains high concentrations of volatile organic compounds (Montgomery 1976). With these characteristics, they can burn readily even at young stand ages, severely aggravate fire hazard problems, and require periodic maintenance to prevent elimination of planted grasses.

HARVESTING FOR AGE-CLASS MANAGEMENT

Rotational harvesting in designated energy management areas is consistent with the concept of age-class management and in some chaparral communities, may have few of the problems associated



Figure 2--Incursion of Eriogonum fasciculatum on a fuelbreak system north of the San Dimas Experimental Forest.

with permanent fuel modification. However, several critical elements must be considered in designing a rotational system.

1. Productivity must be maintained from one rotation to the next or considerable site degradation could occur. Natural regeneration must be sufficient to maintain stocking density and stand composition, and nutrients removed in harvested material must be replaced by natural means.

2. Watershed resource values must be maintained. No fuel hazards may be created by the harvesting operation or incursion of more highly flammable species, and soil erosion must not increase substantially over natural rates.

3. Primary production must be sufficiently high to maintain periodic harvesting on the available land base. The higher the productivity per unit land area, the higher the economic return relative to harvesting costs and the lower the impact on the regional environment.

At present, it is unclear whether these criteria can be satisfied in the different chaparral community types and site conditions. Yet, a number of chaparral species have attributes compatible with periodic harvesting. These include vegetative regeneration from underground lignotubers, rapid growth following disturbance, and associated free-living or symbiotic nitrogen fixation. Harvesting in stands composed of these species is most likely to satisfy the criteria for a successful sustained-yield system. At the same time, harvesting could lead to severe site degradation in some community types and environments.

Chaparral Life History

The life history characteristics of chaparral species reflect a strong adaptation to the periodic occurrence of fire, and these will affect the stand response to harvesting.

A number of important species reproduce from both vegetative structures and seed, including Quercus dumosa, Adenostoma fasciculatum, Ceanothus leucodermis, and Arctostaphylos glandulosa. In stands composed of these species, essentially the same individuals are present before and after a disturbance. They can be expected to regenerate with rapid early growth and maintenance of stocking density, although we have observed some mortality in Adenostoma fasciculatum stands that were found on poor quality sites (Riggan), old when burned, or infected by fungal pathogens while regenerating (Dunn).

Other chaparral species must reproduce from seed stored in the soil, including a number from the genera Ceanothus and Arctostaphylos (such as C. greggii, C. crassifolius, C. megacarpus, and A. glauca). Harvesting these plants can induce epicormic sprouting from remaining stem tissue, but this effect is not reliable.

Most seedling establishment of the dominant chaparral shrubs occurs the first year following fire (Horton and Kraebel 1955). There are important exceptions, such as Quercus dumosa and Cercocarpus betuloides whose establishment is infrequent and probably substantial only in years of high precipitation. The fire-induced germination is probably due to a break in seed dormancy caused by heating (Stone and Juhren 1951, 1953; Hadley 1961). Although heat treatment enhances the germination of seed from several species, not all seed from those species requires treatment. Germination rates of 10 to 20 percent may be expected without heat treatment (Sampson 1944).

Seedling establishment following harvesting is expected to be considerably less than after burning, and greatly reduced stocking density could result. The relatively high densities found after burning may be required to maintain stocking of species that reproduce from seed alone, since seedling mortality from herbivory and water stress can be high in young stands.

If regeneration success is poor, the stand stocking density will remain low and an incursion of grasses or species with easily dispersed seed (such as Salvia mellifera and Eriogonum fasciculatum) could occur. Stands degraded by incursion of these flammable species can propagate wildfires frequently, and if this occurs, a positive feedback may develop with more severe loss of nutrients and production, reductions in stand density, and increasing dominance of the "flash-fuel" species. A single fire in an immature stand of nonsprouting species could cause stand deterioration if sufficient seed for regeneration has not been produced. Arctostaphylos glauca has

apparently been eliminated from large areas of the San Dimas Experimental Forest by fires with a frequency of 15 years (J. S. Horton, pers. commun.).

Stand regeneration has been observed on harvested areas at the Kitchen Creek Research Area on the Cleveland National Forest. In mixed chaparral stands at this site, harvesting has elicited a good regeneration response and stocking density has been maintained (table 2). The harvested areas were cleared in June 1979 and resprout regeneration of Quercus dumosa, Adenostoma fasciculatum, and Ceanothus leucodermis was rapid during the first growing season. Epicormic sprouting was also apparent on some individuals of the obligate seeder, Ceanothus greggii, although their vigor was poor. After two growing seasons, approximately one-third of the Ceanothus greggii showed a vigorous growth of epicormic resprouts. Seedlings of Adenostoma fasciculatum, Quercus dumosa, and Ceanothus greggii were also established during the second growing season (table 2), and it is apparent that a change in stand composition may result. The only mature shrubs exhibiting substantial mortality following harvesting were the Ceanothus greggii. However, seedlings of other species, most notably the Quercus and Adenostoma, have been successfully established, and it is likely that some of these will survive in open areas left by the Ceanothus mortality.

Primary Production

Patterns of primary production have important implications for the design of a chaparral harvesting system. They will affect the selection of appropriate species, sites, and rotation intervals for harvesting.

Production in the chaparral is most limited by plant water stress during the summer drought. Evapotranspiration and other losses deplete the soil moisture in mature stands by the end of the summer, regardless of rainfall during the previous season (Miller and Poole 1979). Sustained high rates of production are most likely in areas of higher elevation and annual precipitation, on more mesic north-facing slopes, and slopes with deeper soils, where water is most available.

Annual precipitation increases markedly with elevation. At the San Dimas Experimental Forest, annual precipitation increases from 660 mm/yr at an elevation of 460 m to 965 mm/yr at 1550 m. Over the same elevation gradient, the decline in air temperature is less; mean daily air temperatures decrease with elevation from 10.2° to 6.3° C during January, and actually increase from 22.3° to 23.1° C during Jul., (Reimann 1959). Furthermore, photosynthesis rates of a number of chaparral species are relatively insensitive to changes in temperature (Oechel and others, in press), so differences in production with elevation are expected to correspond roughly to the increase in water availability.

Table 2--Vegetation composition on the chaparral harvesting research area at Kitchen Creek, Cleveland National Forest. Estimates are averages from four, 1 by 75 m belt transects located within the north, 0.5-ha hand-cleared area

	<u>Q. dumosa</u>	<u>A. fasciculatum</u>	<u>C. greggii</u>	<u>Total</u>
	<u>Stocking density (per ha)</u>			
Preharvest composition (34-year-old stand)	1230	2100	7200	10,530
Postharvest (2-year-old stand)				
Resprouts	1230	2000	2270	5,500
Dead	0	100	4930	5,030
Seedlings	1730	400	2530	4,660
Total live	2960	2400	4800	10,160
	<u>Relative composition (percent)</u>			
Preharvest	12	20	68	
Postharvest	29	24	47	

Chaparral communities on north-facing aspects develop larger leaf areas (Krause and Kummerow 1977) and apparently sustain higher rates of production than those on south-facing slopes. These differences result from the lower levels of air temperature, direct solar radiation, evaporative demand, and plant water stress on the north-facing aspect. On south-facing slopes at San Limas, maximum daily air temperatures under the chaparral canopy can be 6° to 12° C higher and evaporation rates 15 percent greater than on north-facing aspects (Miller 1947). In areas of chaparral with relatively high precipitation rates (greater than 650 mm/yr), the north-facing slope can have roughly 30 percent more available water in the soil (Miller 1947). In drier areas, the larger leaf area can actually dry the soil more rapidly on the north-facing aspect (Ng and Miller 1980) while maintaining less severe levels of plant water stress (Krause and Kummerow 1977).

The more mesic sites in the chaparral are frequently dominated by mixed-species stands with a large component of Quercus dumosa (for example, see Krause and Kummerow 1977). This species has a rate of annual carbon uptake per unit leaf tissue that is among the highest measured in the evergreen chaparral species (Oechel and Nustafa 1979). It is also able to maintain relatively high leaf areas per area of crown coverage (Krause and Kummerow 1977). Together these properties give it a relatively high rate of net primary production. Rates of biomass accumulation as high as 2.8 MT/ha have been observed in resprouting stands the first year following burning (Riggan and Lopez 1981). Relatively high rates of biomass accumulation are also apparent in well-stocked stands of some obligate-seeder Ceanothus species. Biomass accumulates at rates as high as 4.0 MT/ha-yr in C. crassifolius stands at the San Dimas Experimental forest (J. K. Weaver and Riggan, unpubl. data) and 2.7 MT/ha-yr in C. megacarpus near Santa Barbara

(Schlesinger and Gill 1980) (table 1). However, harvesting in these productive Ceanothus stands could result in serious regeneration problems.

Rates of biomass accumulation may decline in older stands of chaparral as stand nutrients are sequestered in organic material and the stand accumulates a high proportion of respiring woody biomass. If this is true, long-term yield could possibly be improved by harvesting a stand at the culmination of the early period of rapid growth. At present, there is little information to characterize the trends of biomass accumulation during stand development, but biomass is known to accumulate at high rates through age 20 in Ceanothus megacarpus.

Nutrient Cycling

The availability of nitrogen in chaparral soils can limit the growth and production of a number of species, including Adenostoma fasciculatum, Arctostaphylos glandulosa, and several Ceanothus species (Vlamis and others 1954, 1958; Hellmers and others 1955). Phosphorus supply may also be marginal for growth of native shrubs (Kummerow, pers. commun.; Hellmers and others 1955).

harvesting could have a major impact upon the nutrient balance in the chaparral ecosystem by removing large quantities of nutrients in harvested material and interfering with natural processes of nutrient input. Adverse effects upon nutrient availability would limit the production in subsequent rotations and the success of the harvesting system.

The impact of harvesting nutrient losses must be evaluated in relation to the naturally high rates of fire-associated loss. In an ideal harvesting system the community is maintained in a

young state with low dead fuel accumulations, and this should lower its susceptibility to wildfire. The reduction of fire-associated losses could be greater than the losses due to harvesting.

Fire-associated nitrogen losses occur by volatilization and subsequent erosion, and these can be considerable. Volatilization losses during moderate-intensity prescribed fires can remove 10 to 25 percent of the stand's nitrogen content, primarily from fine fuels, ground litter, and the upper soil profile (table 3). Nitrogen loss during intense wildfires could be even greater. Harvesting these stands would remove the nitrogen in the standing vegetation but would not remove nutrients in the litter or soil, so a less severe impact on the nutrient balance of the system should result. Nutrient losses from harvesting could also be reduced by allowing the cut chaparral to dry and partially defoliate on site before it is processed. Foliage contains one-third of the nitrogen in the aboveground vegetation (Riggan and Lopez 1981), and this need not be removed.

Fire-associated erosion losses are potentially an even larger path of nitrogen loss. Hill slope sediment yield can increase 200-fold the first year following fire (Unpublished U.S. Forest Service report cited by Wells 1981) as the soil surface is exposed to eroding forces and the structure and infiltration properties of the soil are altered. During chaparral fires, a water repellent layer can form several centimeters below the soil surface when hydrophobic organic compounds distill downward and condense in the soil profile (DeBano 1981). The water repellent soil confines water in the upper wettable layer, with an increase in pore pressure and reduced internal friction. The instability formed can result in soil loss by mass wasting and miniature debris flows that form rills (Wells 1981). Loss of

organic matter and alteration of soil clays during burning (Wells 1981) can also reduce soil stability and accelerate erosion.

Extremely high rates of erosion loss are possible. For example, losses of 210 m³/ha (2.1 cm of soil) and 830 m³/ha (8.3 cm of soil) have been estimated for the Sweetwater River watershed in San Diego County and the Little Dalton Canyon watershed at the San Dimas Experimental Forest, respectively (Rowe and others 1949). If this material originates from surface soils, 830 m³/ha of sediment would carry with it approximately 2500 kg of nitrogen per ha (assuming 0.2 percent nitrogen), and cause a catastrophic change in site nitrogen.

Hill slope erosion losses following harvesting are expected to be considerably less than those associated with wildfire if harvesting equipment does not disturb the soil surface. Harvesting would temporarily remove the protective cover of the vegetation canopy, but the severe water repellency and changes in soil structure associated with intense heating would not occur. A relatively protective litter layer would also remain in stands of *Quercus dumosa*.

It appears that nutrient losses from harvesting are considerably less than those associated with burning at a comparable frequency. However, harvesting could take place on a rotation interval that is less than the frequency of fire, if short rotations are used to optimize long-term production and yield. By contrast, wildfires generally occur in older stands with larger accumulations of dead fuel. Increasing the frequency of harvesting also increases the export of nutrients, and a point is reached where benefits from maintaining the stand in a young, productive state are outweighed by a decline in productivity from nutrient loss.

Table 3--Comparison of nitrogen distributions and losses from fire-associated volatilization and biomass harvesting in contrasting chaparral types. Estimates are for 25-year-old *Adenostoma*-dominated chaparral in the Los Padres National Forest northeast of Santa Maria, California (DeBano and Conrad 1978) and 35-year-old *Quercus dumosa*-dominated chaparral in the Cleveland National Forest at Kitchen Creek (Riggan and Lopez 1981). Harvesting is assumed to remove the aboveground plant only. Erosion losses are not considered.

	<i>Adenostoma</i> chaparral			<i>Quercus dumosa</i> chaparral		
	Distribution	Losses from		Distribution	Losses from	
		volatilization	Harvesting		volatilization	Harvesting
Aboveground vegetation	134	} 161 +8 109	134	88	} 61 +317 378	8
Litter	147		-	382		-
Soil (0 to 10 cm)	<u>1140</u>	<u>36</u>	<u>-</u>	<u>1586</u>	<u>138</u>	<u>-</u>
Total	1426	145	134	2056	516	88

The mechanisms of nitrogen input and processes that affect nitrogen availability must also be considered in the design of a harvesting system. Harvesting may interfere with natural nitrogen replacement in some chaparral communities, and the behavior of these processes will affect the allowable frequency of harvesting and location of energy management areas.

Nitrogen enters the system in precipitation and dryfall, and by N₂ fixation associated with post-fire legumes, free-living microbes, and symbiotic associations with members of the genera Ceanothus and Cercocarpus. Precipitation inputs are low, generally less than 8.0 kg/ha-yr (Liljestrand and Morgan 1978), and are generally unaffected by management.

Legumes of the genera Lupinus and Lotus are common components of the profuse annual and perennial flora found after chaparral fires. They are relatively short-lived and are host to symbiotic fixation with rates in the range of 3 to 40 kg/ha-yr (Dunn and Poth 1979; Poth, pers. commun.). Higher rates of N₂ fixation may be associated with members of the genera Ceanothus and Cercocarpus. Studies in the greenhouse and under mesic field conditions have shown that substantial rates of fixation can occur (Hellmers and Kelleher 1959, Vlamis and others 1958, Youngberg and Wollum 1976). However, estimates of N₂ fixation by Ceanothus in southern California chaparral are uncertain. Annual nitrogen accretion over 13 years in developing Ceanothus crassifolius was estimated to be 49 kg/ha-yr (Zinke 1969), but process study estimates in mature stands and 1-year-old seedlings have shown only low rates (Kummerow and others 1978; Dunn and Poth, pers. commun.). Substantial rates of N₂ fixation have been measured in 4-year-old Ceanothus crassifolius seedlings at San Dimas (Dunn and Poth, pers. commun.), and this suggests that N₂ fixation may be restricted to established young stands.

Dinitrogen fixation by free-living microbes may also be important in chaparral soils, although process studies have yet to show sustained fixation by this mechanism in the field. Lysimeter studies at San Dimas have shown that the annual nitrogen accretion over 13 years associated with Quercus dumosa, 38 kg/ha-yr, and Eriogonum fasciculatum, 32 kg/ha-yr, can be substantial. Over the same period, lysimeters kept free of vegetation lost nitrogen at an average of 26 kg/ha-yr (Zinke 1969).

If periodic harvesting reduces the occurrence of fire on a site, the establishment of postfire legumes would be precluded and the establishment of Ceanothus seedlings could be greatly reduced. A considerable impairment of N₂ fixation in the stand could result.

Dinitrogen fixation will affect the suitability of stands for harvesting and the stand response to different rotation intervals. Stands with more mesic environments and those comprised of

resprouting Ceanothus or Quercus species are expected to have relatively high rates of nitrogen replacement. Dinitrogen fixation rates may be highest when these are relatively young, declining as they mature and senesce. If so, harvesting with a short rotation interval would maintain the stand in a state with high N₂ fixation rates, and increase long-term nitrogen accretion. Periodic harvesting could also result in more favorable soil-water conditions, warmer soil temperatures during the spring, and a favorable carbohydrate balance in resprouting individuals. Each of these effects would be conducive to N₂ fixation and could counter the loss of nitrogen in harvested biomass.

Land Area Requirements

If the development of chaparral harvesting as a source of renewable wood energy is to provide a significant amount of the energy needed by California, the area of land managed for this purpose must be large. Approximately 1000 mi² of relatively high-productivity chaparral would be required to supply the residential energy requirements for a city the size of Pasadena, California.³ The size of this undertaking would greatly magnify the impacts of harvesting. Other considerations such as visual impacts and erosion from roads and equipment landings would have to be assessed for any specific operational program, and these might limit its scope and practicality.

RESEARCH NEEDS

A number of important research problems should be addressed concurrently with the development and demonstration of chaparral harvesting.

1. Adverse impacts of harvesting may limit production in subsequent rotations or create other resource management problems. Research is needed to determine the following for major chaparral community types: (a) the probability of site

³Estimated as follows:

Residential energy use in the City of Pasadena (1980 population of 119,000, 50,000 residences, 4700 kwh/yr average use) is 2.35×10^8 kwh/yr (City of Pasadena, Water and Power Department, 1980 Annual Report). With reference to a 3.3×10^8 kwh/yr, hybrid geothermal-wood energy powerplant using 75 percent wood energy and 2.3×10^5 MT/yr (U.S. Dep. Agric., Forest Serv. 1978), expected energy yield from biomass is 1.1×10^3 kwh/MT, and an annual harvest of 2.1×10^5 MT is required. Assuming chaparral with 50 MT/ha, and harvesting on one-third the land area with a 20-year rotation interval, the necessary sustained yield of wood energy would require a land area of 2.5×10^5 ha or 1000 mi². Eight percent of the managed chaparral would be less than 5 years of age at any time.

degradation from incursion of highly flammable species, such as sage or buckwheat; (b) the magnitude of nutrient loss in harvested material and interference with nitrogen fixation; (c) loss of stocking density due to poor seedling regeneration; and (d) the magnitude of erosion losses due to soil disturbance by equipment.

2. Existing biomass accumulations and rates of net primary production are not well known, nor are there good inventory methods or predictive models available. Research is needed to (a) estimate rates of biomass accumulation in major community types and identify the most productive sites, (b) estimate the rates of biomass accumulation during stand development, and (c) develop predictive models from which guidelines could be made for selection of energy management locations.

3. Research is needed to determine the effects of short rotation intervals on stand production, regeneration, and nitrogen balance. The patterns of nitrogen replacement, seed production, and stand susceptibility to fire during stand development should be identified.

SUMMARY

The characteristic life histories, patterns of primary production, and nutrient cycling in a chaparral community will determine its response to harvesting. A number of Quercus and Ceanothus species such as Q. dumosa, Q. chrysolepis, Q. wislizenii, and C. leucodermis may have attributes compatible with periodic harvesting. These include vegetative regeneration from lignotubers or burls, rapid growth following disturbance, and associated free-living or symbiotic nitrogen fixation. Several of the Ceanothus species which reproduce from seed alone (e.g., C. crassifolius and C. megacarpus) have relatively high rates of biomass accumulation and may support symbiotic N₂ fixation, but these are probably not compatible with harvesting because of poor regeneration success in the absence of fire. Stands of Adenostoma fasciculatum generally have lower rates of biomass production and nitrogen input, and could be degraded by periodic harvesting.

Serious site degradation could result from periodic harvesting if stand stocking density is not maintained. Open stands are subject to incursion of "flash-fuel" subshrubs and grasses that could propagate fires frequently. This would accelerate nutrient and soil losses and further reduce stocking density and productivity. Similarly, burning through any residual harvesting slash could seriously degrade the stand.

Chaparral age-class management employing harvesting on selected sites could reduce the incidence of severe wildfires and the associated erosion. The reduction of fire-associated nutrient losses may be greater than the loss of nutrients in harvested biomass.

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