Journal of Park and Recreation Administration
Fall 2014
Volume 32, Number 3
pp. 29–48

Computer Simulation Modeling to Determine Trailhead Quotas for Overnight Wilderness Visitor Use

Robert Van Kirk
Steven Martin
Kai Ross
Mark Douglas

EXECUTIVE SUMMARY: Limits on overnight visitor use may be needed when demand is very high and other management tools alone are inadequate to protect resource and experiential conditions. In the wilderness, trailhead quotas may be an effective management tool that allows for more visitor autonomy. For trailhead quotas to be effective; however, managers must have a very good understanding of the relationship between the trailhead origin of trips and the resulting spatiotemporal distribution of users. Simulation modeling can accurately determine this relationship, thus allowing managers to set informed and appropriate trailhead quotas. This study showed how a simulation model can be used to 1) monitor the distribution of overnight wilderness visitors in a large wilderness area with a complex trails network and 2) achieve an informed redistribution of overnight visitor use that reduces the number of areas that are overcapacity while still accommodating the same overall amount and the same temporal distribution of visitor use.

KEYWORDS: *simulation model, trailhead quotas, wilderness use*

AUTHORS: Robert Van Kirk is with the Henry's Fork Foundation, Ashton ID, 83420, robert.vankirk@humboldt.edu. Steven Martin is with the Department of Environmental Science & Management, Humboldt State University. Kai Ross is with the Department of Quantitative Ecology and Resource Management, University of Washington. Mark Douglas is with the Department of Society and Conservation, University of Montana.

ACKNOWLEDGMENTS: The National Park Service, through a grant from the Yosemite Conservancy, provided funding for this study. We wish to thank Bret Meldrum, Mark Fincher, Paul Gallez, Mark Marschall, David Pettebone, Ken Watson, Bill Kuhn, Jay Sammer, Martijn Ouborg, and Naomi Chakrin, along with the wilderness permit distribution team and personnel at all park entrance/exit stations for their assistance with the project. Surveys were administered

under Office of Management and Budget permit 1024-0224 NPS #09-014 and National Park Service scientific research and collecting permit YOSE 2010 SCI 0048 Study ID 0041.

Over the past several decades, demand for wilderness recreation has challenged managers of protected areas throughout the world to accommodate use while maintaining both ecological integrity and the quality of the wilderness experience itself. With the Wilderness Act of 1964, the U.S. Congress established the National Wilderness Preservation System, protecting vast roadless areas with significant recreational, ecological, geological, scientific, educational, scenic or historical value. Although the Wilderness Act served to establish the system, it did not establish specific management practices for protecting the resources and values from use and overuse by the visitors for whom it was, in part, created.

The Act directed the managing agencies to be responsible for preserving the wilderness character of the area. Recreation visitor use, or overuse, may be a source of impact to wilderness qualities and values such as naturalness and solitude (for detailed reviews see Hammitt & Cole, 1998; Leung & Marion, 2000; Cole, 2009; Monz, Cole, Leung, & Marion, 2010). In some wilderness areas, the spatiotemporal distribution of use is such that visitors are heavily concentrated in popular locations. As Dawson and Hendee (2009, p. 378) point out, some of these "popular locations . . . may be sensitive to physical impacts from use and intrusions on solitude," leading to any number of management responses to minimize the negative effects of large numbers of visitors.

Visitor Management

Potential visitor management strategies and techniques generally fall into two broad categories: 1) influencing visitor access, such as daily trailhead quotas or purposely making trail access more difficult, and 2) influencing visitor behaviors and activities, such as prohibiting campfires or Leave No Trace education efforts. Within each of these categories, specific actions fall along a continuum of direct to indirect management, reflecting the degree to which the management action restricts or preserves the behavioral autonomy of the visitor. Direct visitor management is more restrictive and regulatory, while indirect management relies on approaches such as information and education to influence decisions made by visitors, or on the presence or design of facilities in an area, such as choosing whether or not to provide bridge access across a river (Manning & Lime, 2000). Generally, the more overt and regulatory the management presence in the visitor experience, the more potential for adverse impact to that wilderness experience. Direct management actions have greater potential to negatively impact a visitor's wilderness experience by detracting from "the sense of primitive and unconfined recreation called for in the Wilderness Act" and "diminishing the sense of experiencing wilderness and facing challenges on one's own" (Dawson & Hendee, 2009, p. 453).

One way to relieve some of what Dawson and Hendee call the "tension between recreation and regulation" is to conduct as much of the regulatory management as possible outside of the wilderness area, consequently maximizing visitor autonomy once inside the wilderness. Trailhead quotas are one way of doing this. Although limiting and rationing use to a wilderness by way of daily entry quotas may be a very direct and regulatory approach to visitor management, it preserves a greater degree of visitor freedom once in the wilderness (e.g. itinerary flexibility, campsite choice). In heavily used wilderness areas, where even the best and most carefully implemented indirect management tools might still be ineffective in the absence of visitor use limits, trailhead quotas may be seen as an effective frontcountry mechanism for achieving desired backcountry objectives such as reduced ecological impacts and increased opportunities for solitude, while preserving visitor freedom inside the wilderness. Managers of wilderness areas administered by the

National Park Service and the U.S. Forest Service throughout the Sierra Nevada mountains of California commonly use daily trailhead quotas to limit use, thereby allowing visitors greater autonomy and flexibility to tailor their trip itinerary spontaneously once inside the wilderness.

If daily trailhead quotas are to be used, the next question is, how are those quotas determined? By way of tailored trailhead quotas, managers are attempting to achieve a desired spatiotemporal distribution of visitor use. But the complexity of travel routes and variability of visitors' decisions make it extremely difficult for managers to be able to predict with a reasonable degree of certainty the spatiotemporal distribution of visitors from a given entry-point distribution. Furthermore, even when visitors are required to specify a trip itinerary on their backcountry permit, it has long been known that visitors frequently deviate from their intended itinerary (van Wagtendonk & Benedict, 1980; Parsons, Stohlgren, & Kraushaar, 1982), so the relationship between trailhead-of-origin and location of backcountry use determined from permit itineraries is not the actual relationship realized on the ground. Accurately determining this relationship from trial-and-error experimentation would be costly, time-consuming, and influenced by uncontrolled external factors (Dawson & Hendee, 2009, pp. 478–479).

Thus, when dealing with wilderness recreation systems that involve both spatial complexity and the uncertainties of visitor behavior, computer simulation has become a standard tool that allows researchers and managers not only to better understand the spatiotemporal distribution of visitors, but to "predict how distributions of visitor use are likely to change in response to management actions" and to "test the feasibility and effectiveness of management plan alternatives" (Cole, Cahill, & Hof, 2005). Different management scenarios can be tested in a comprehensive, low-cost way, free of public and political consequences, and managers can see what effects their various alternatives would have in a variety of future use conditions (Cole & Daniel, 2003; Lawson, Manning, Valliere, & Wang, 2003; Dawson & Hendee, 2009).

One of the first models used for wilderness management was the Wilderness Use Simulation Model (WUSM) developed by Smith and Krutilla (1976) and applied in many different settings (Schecter & Lucas, 1978; van Wagtendonk, 1978; Potter & Manning, 1984). The WUSM simulated user behavior along trails or other travel routes, for the primary purpose of quantifying encounters between parties (van Wagtendonk, 2003). Applications of the WUSM focused on the effects of use on the recreational experience of wilderness users themselves rather than on impacts to physical or biological resources. Primary model inputs were definition of travel routes, estimated travel time over each route segment, temporal and spatial distribution of parties entering the wilderness, and number of users (Potter & Manning, 1984). Model inputs were usually derived from visitor registers, permits, and interviews, which generally resulted in a relatively small set of fixed travel itineraries being used in the model. However, an application of the WUSM to boating on the Colorado River employed computer simulation to generate trip itineraries, in order to obtain an essentially limitless set of possible trips that could be taken (Underhill, Xaba, & Borkan, 1986).

The next generation of recreational-use simulations models was implemented in the software ExtendSim, an object-oriented, discrete-event, dynamic simulation package (Imagine That, 2010). ExtendSim models have been used in many parks and wilderness areas, including Acadia National Park (Wang & Manning, 1999), Arches National Park (Lawson et al., 2003), Isle Royale National Park (Lawson, Kiely, & Manning, 2004), and the John Muir Wilderness (Lawson, Itami, Gimblett, & Manning, 2006). Although most of these applications still focused on "social carrying capacity" (Lawson et al., 2003) rather than on natural-resource carrying capacity, the flexibility of the ExtendSim simulation environment and increased computational power allowed the model to track and record data such as the number of visitors camping each night at a given location, which could be used to assess effects of use on physical and biological resources. Higher

computational efficiency also increased the number of random ("stochastic") components that could be included and allowed a larger number of independent stochastic replications to be performed. This increased the number of different outcomes that could be generated from a given set of inputs and increased statistical power in comparing model outputs to actual observations. However, trip itineraries were still largely determined from interviews or permits, again limiting the number of different itineraries included in the model and the ability of the model to dynamically incorporate changes in visitor behavior once a simulated party has entered the wilderness (Lawson et al., 2006).

These limitations have been addressed by development of agent-based models such as RBSim, in which individual users interact dynamically with the physical environment (Itami et al., 2003). Known as "individual-based" models in the ecology literature, agent-based models have been widely applied to fish and wildlife management (e.g., Schumaker et al. 2014). These "virtual reality" models (Bishop & Gimblett, 2000) use Geographic Information Systems (GIS) to accurately simulate the physical environment encountered by users and specify a set of behavioral rules that govern how simulated users react to their environment. For example, the rules might specify that visitors are likely to stop at a scenic viewpoint or avoid climbing a steep section of trail late in the day when they are tired (Gimblett, Richards, & Itami, 2001). Agent-based models are limited only by the amount of GIS data and complexity in the behavioral rules that are included in the model, but increased realism comes at the cost of models that are difficult to parameterize, understand and defend (Schumaker et al. 2014).

One of the earliest applications of trailhead quotas was in the wilderness of Yosemite National Park. In response to overuse in the Yosemite wilderness, a mandatory permit system was implemented in 1972. Subsequently, the wilderness was divided into 53 management zones (Figure 1), and an overnight visitor use capacity was established for each zone in 1977 (van Wagtendonk, 1986). In order to minimize the probability that visitor use would exceed zone capacities, without imposing excessive regulation on users once they enter the wilderness, a trailhead quota system was implemented in 1977 (van Wagtendonk, 1981; van Wagtendonk & Coho, 1986), and remains in effect today. All overnight visitors to the Yosemite Wilderness are required to obtain a wilderness permit. When the permit is issued, visitors indicate their intended trip itinerary, including number of nights and intended campsite location for each night, at the resolution of the wilderness travel zone. Trailhead quotas are enforced through the permit system, but visitors are not required to adhere to their intended itinerary once in the wilderness; they may shorten or lengthen their trip, and they may choose to camp in different locations than originally intended. Since wilderness use estimates (both overall and by zone) are based on the intended trip itineraries contained in the permit database, deviations from intended itineraries affect the accuracy of the overall, and zone-by-zone, use estimates. Additionally, since many management actions (trailhead quotas being probably the most obvious) are based on the spatial distribution of visitors, spatial deviations from intended itineraries affect the efficacy of the trailhead quotas and other spatially-based management actions.

The objectives of this study were to a) construct an overnight wilderness use simulation model that uses dynamic rather than fixed itineraries and incorporates visitor deviation from intended itineraries, b) validate and apply the model to the Yosemite Wilderness to predict visitor use and probabilities of overuse at the resolution of each wilderness zone on each night of the season ("zone-night"), c) quantify the effect of itinerary deviation on use estimates, d) determine the dependence of zone use on trailhead of origin, and e) determine whether adjustment of trailhead quotas can reduce probability of overuse while accommodating the current level and temporal distribution of visitor use. Although we have applied the model to the Yosemite Wilderness, the model framework is applicable to any management setting in which intended travel itineraries and deviation characteristics are known.

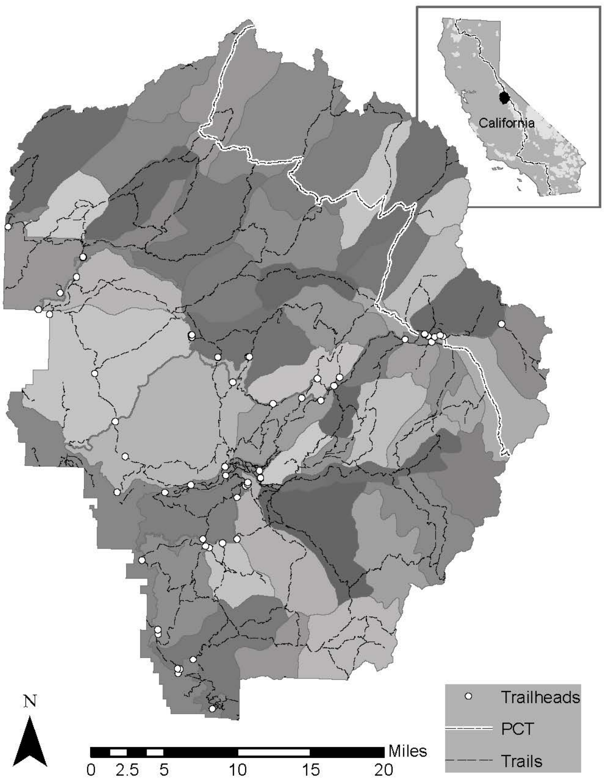

Figure 1. Map of Yosemite National Park, showing wilderness travel zones, trailheads, and trails, including the Pacific Crest Trail (PCT).

Method

Study Area

The Yosemite Wilderness includes 281,855 ha, nearly 95% of the park, situated on the western slope of the Sierra Nevada Mountains (Figure 1). Sixty-four trailheads provide access to 1,112 km of trail. An additional 46 trailheads feed 669 km of trail on adjacent U.S. Forest Service (USFS) wilderness lands. The Emigrant Wilderness borders the Yosemite Wilderness to the north, as does the Hoover Wilderness to the east, and the Ansel Adams Wilderness to the south. Two popular long distance hiking trails traverse Yosemite's wilderness; the John Muir Trail stretches from Yosemite Valley south to Mount Whitney, and 80 km of the Pacific Crest National Scenic Trail (Fig. 1) are within the park (van Wagtendonk, 2004). Peak use and the demands it places on the wilderness resource necessitate use limits. Trailhead quotas are enforced through the wilderness permit system. Permit reservations may be made up to 24 weeks in advance of the date of entry into the wilderness. Daily, 60% of each trailhead quota is allocated to reservation, with 40% left for first-come first-served access in person.

Description of Basic Model and Itinerary Simulation

Our goal was to develop a stochastic simulation model that incorporated the advantages of agent-based models, in which users adjust their behavior dynamically once

they begin their wilderness trip, while retaining the simplicity and statistical defensibility of parameterizing the model with information based on visitor surveys and permits. We also desired to use a platform that was familiar to managers and to incorporate only as much spatio-temporal resolution as was necessary to inform management, which in Yosemite, occurs at the level of trailheads, wilderness zones, and nights spent in the wilderness. Thus, we built the model in ExtendSim and parameterized it with data from wilderness permits and visitor interviews. However, we developed an innovative algorithm that simulated individual travel itineraries dynamically based on probabilities of transitioning from a particular trailhead to a wilderness zone on the first day of the trip and then from zone to zone or zone to exit on each subsequent day. Furthermore, we included a procedure that allowed parties to deviate from their intended trip itinerary once in the wilderness. These algorithms simulate a theoretically infinite number of different itineraries from a very small set of empirically determined probability distributions, balancing realism and simplicity. Model details are given in Ross (2011); we provide a less detailed description here.

Distributions of party size, trailhead selection, and trip date were created empirically from the Yosemite wilderness permit database, using information from all 14,497 parties that started trips during the 153-day summer season (May 1 through September 30) in 2010 and intended to spend at least one night in the Yosemite wilderness. Trip date was assigned deterministically in the model to match the observed temporal distribution of use; all other characteristics were assigned or simulated randomly. Party size, trip date, and trailhead-of-origin were assigned at the initiation of a simulated trip (Figure 2). Trailheads were assigned randomly, according to observed probabilities of trailhead use. If random selection of a trailhead from the empirical distribution resulted in assignment of a party to a trailhead already at quota, that trailhead was removed from the empirical distribution, and a new trailhead was randomly selected. On average, this had the effect of assigning to the party the next most popular trailhead that was available. Once a party was assigned a starting trailhead, an initial wilderness zone was randomly selected from the empirical distribution of zones reachable from that trailhead, and the party spent its first night in that zone. For example, the permit database indicated that 95.1% of all parties starting trips at trailhead 36 intended to spend their first night in zone 75 (Figure 3), so in the model, a party starting at trailhead 36 had a 0.951 probability of spending its first night in zone 75.

Instead of creating a fixed set of travel itineraries, travel route and trip duration for each party were simulated dynamically according to a transition-probability matrix that was created from all 14,497 intended itineraries in the permit database. The entries in the matrix were the conditional probabilities of a party spending its next night in each of the wilderness zones, given its current location. For example, entry [75,65] in this matrix was 0.08349, indicating that if a party was currently in zone 75, it intended to spend its next night in zone 65 with a probability of 0.08349 (Figure 3). Additional transition matrices and user attribute distributions were created for Yosemite wilderness use that originated at surrounding USFS trailheads, using permit data where available and visitor survey responses (n = 147) otherwise. So that we did not have to preselect trip durations, we included a state in the transition matrix that represented ending the trip. The model multiplies the number of nights stayed in the zone by the size of the party to track how many visitor nights are spent in each zone on each night.

Prior to accounting for itinerary deviation in the model, we used statistical verification and validation to ensure that model algorithms were implemented correctly and model-simulated intended-trip values matched observed intended-trip values. Based on behavior of variance in model outputs, we used the results of 1,000 independent stochastic replicates for verification and validation. We used a significance level of $\alpha = 0.05$ for verification and validation tests, as well as for all other statistical analyses.

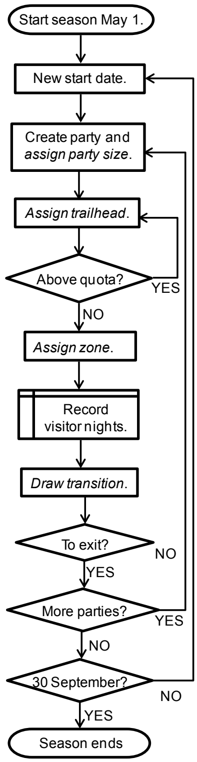

Figure 2. Flow Diagram of Simulation Model.
Italics indicate stochastic elements.

Deviation Data and Algorithm

We distributed a survey instrument to all parties that received a wilderness permit in Yosemite on a stratified random sample of days during the 2010 summer season. Surveys consisted of map diaries on which respondents marked their actual trip routes, from entry trailhead to campsite(s) to exit trailhead, indicating each campsite's location with a circled number corresponding to the night of their trip (Douglas, 2011). We distributed the survey to 2,755 overnight parties, of which 1,134 (41.2%) returned the survey. Of the returned surveys, 1,123 could be compared to a complete, intended trip itinerary in the wilderness permit database. These usable surveys represented 7.7% of all parties and 9.0% of all visitor-nights. Potential non-response bias was evaluated by contacting a sample of parties (n = 75) that obtained but did not return a survey. Statistical tests showed no evidence of non-response bias (Douglas, 2011).

To evaluate the degree to which visitors deviated from their intended itinerary (as detailed in the park's permit database), we compared actual trip itineraries from returned surveys to the corresponding intended trip itineraries from the park's wilderness permit database. Temporal deviations were defined as the difference between actual and intended number of nights spent in the Yosemite Wilderness, including those resulting from parties that obtained a permit but did actually enter the wilderness. A spatial deviation was defined as any difference between the actual wilderness travel zone in which a party camped and the zone in which the party intended to camp, including difference in order. For example, a particular four-night itinerary in the permit database intended that the first night was

spent in zone 75, the next two nights in zone 66, and the fourth night in zone 59 (Figure 3), (i.e., the trip, 75,66,66,59). An actual trip of (75,66,59) would have a temporal deviation of -1 days but no spatial deviation. The trip (75,66,59,66) would constitute a spatial but not temporal deviation, and the trip (75,66) would deviation both spatially and temporally.

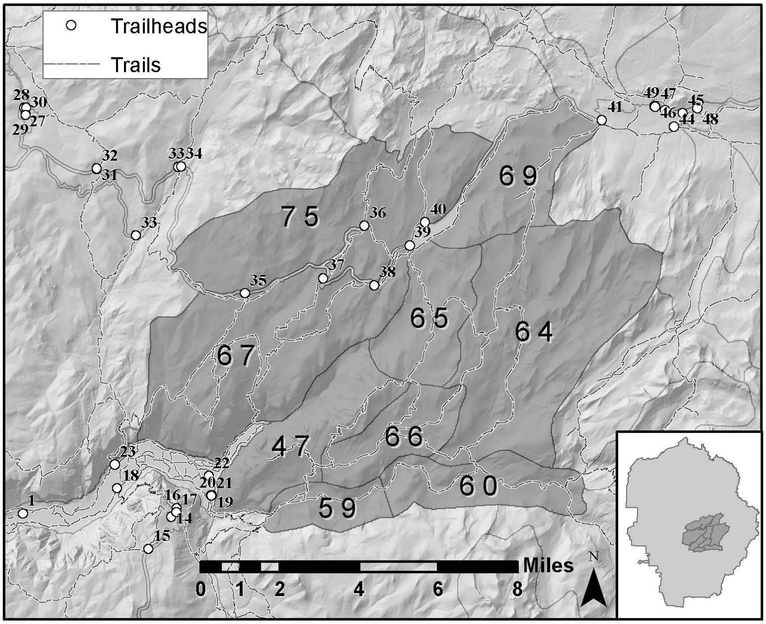

Figure 3. Close-up view of zones and trailheads near the center of the park. Zone and trailhead identification numbers correspond to those used in Figures 4 and 5.

Temporal deviation was modeled by changing the probability of exiting the wilderness in the transition matrix, without changing the relative transition probabilities among the zones. The factor by which exit probabilities were adjusted was determined by requiring mean trip duration produced by the model to match mean trip duration of actual parties, when averaged over all parties over the entire season. This latter estimate was produced by adjusting intended trip duration of all trips in the permit database by the temporal deviation characteristics observed in the sample.

The distribution of spatial deviation probabilities across night of trip observed in the sample was applied stochastically in the model. If a party was randomly selected to be a spatial deviant, a new transition was selected from the transition matrix, without replacement of the transition originally drawn. This algorithm forced the party to do something other than what it originally intended, but it did so in a way that preserved relative transition probabilities, so that the resulting “actual” itineraries were realistic.

Model Scenarios

We performed 1,000 independent, stochastic, season-long simulations under each of five scenarios: 1) *validation*, 2) *current conditions*, 3) *current conditions including external influence,* 4) *maximum allowed use*, and 5) a *redistribution* scenario that moved starting locations of trips away from the most popular trailheads (Table 1). All scenarios were parameterized with data from the 2010 summer season but differed from one another in

inclusion of itinerary deviation, inclusion of use originating at trailheads outside of the park, and distribution of party start dates and trailheads of origin (Table 1). All scenarios were run for 153 time-steps representing May 1 through September 30. The main output for each scenario is a table containing the mean and standard deviation, across all stochastic simulations, of visitor nights spent in each zone on each night across the entire season, and a second table containing how many visitor nights each trailhead contributed to each wilderness zone. Mean use for a given scenario was defined as the mean over the 1,000 simulations. The probability of use exceeding capacity in a given zone on a given night was defined as the fraction of the 1,000 simulations in which the zone capacity was exceeded on that night. The attributes of each party in each simulation were recorded so that we could relate the number of visitors camping in each zone on each night to trailhead-of-origin.

Table 1

Summary of Model Scenario Parameters and Results

	Model scenario				
	Validation	Current conditions	Current conditions (including external trailheads)	Maximum allowable use	Redistribution
Itinerary deviation	NO	YES	YES	YES	YES
Use from trailheads outside park	NO	NO	YES	NO	NO
No. of parties each day	observed	observed	observed	Maximum quota at each trailhead	observed
Distribution of starting trailheads	observed	observed	observed	Maximum quota at each trailhead	3,575 parties moved from high- to low-use trailheads
Total season-long use (mean visitor nights over 1000 simulations)	103,941	89,997	100,007	345,780	89,997
Percentage of zone-nights with at least 30% probability of capacity exceedance	NA	1.6%	1.7%	27.6%	0.099%

The validation model was parameterized directly from the permit database, without accounting for itinerary deviation or use originating from outside of the park. The current conditions scenario reflected the best attempt at simulating actual overnight Yosemite wilderness visitor use patterns, parameterized by trailhead of entry, entry date, party size, trip length, and probabilistically simulated travel throughout the wilderness zones. This scenario simulated actual Yosemite wilderness visitor use in 2010 from parties that originated their trip at a trailhead in the park and served as a baseline scenario to which the others could be compared. We calculated the effect of itinerary deviation by comparing output of the current-condition scenario with that of the validation scenario. To quantify the effect of external use, we performed a second version of the current-condition scenario that included parties that originated their trip at a USFS trailhead outside of Yosemite.

The maximum-allowed-use scenario evaluated the effects of filling every trailhead quota on every day of the season. Since the same number of visitors entered every day, this scenario represented a stable equilibrium of wilderness visitation. To eliminate confounding of the zone use-trailhead relationship by use originating at trailheads outside of the park, we did not include these external trips in the maximum-allowed-use scenario. This scenario had two objectives. The first was to identify the total amount of overnight use in each zone that could occur under the current trailhead quota system, if every trailhead quota is filled on every night of the season. The second objective was to generate the "true" dependence of zone use on trailhead of origin. The trailhead-zone use relationship generated by the current-conditions scenario primarily reflects trailhead popularity and only secondarily reflects trailhead quota, since the most popular trailheads are generally filled to quota on most nights of the season, whereas many other trailhead quotas are either filled only on the most busy weekends or are never filled at all. The maximum-allowed-use scenario eliminates both temporal and spatial preference for trailhead selection and thus generates a relationship between zone use and trailhead that is based only the quotas and the accessibility of zones from trailheads.

The redistribution scenario involved 1) identifying trailheads that contributed most to zone-capacity exceedance under current conditions, 2) using the model to determine how many parties would need to be moved from these trailheads so that use in each zone did not exceed capacity on any given night in more than 30% of all simulations, and 3) redistributing the required number of parties from these high-use trailheads to low-use trailheads. We reassigned parties that were turned away from the high-use trailheads by using trailhead selection probabilities that were inversely proportional to those observed. This had the effect of redistributing excess use from the most popular trailheads in the park to the least popular trailheads. For consistency in comparison, we did not include use originating from outside of the park in this scenario.

Results

Model Validation

There were no significant differences in mean party size, trip duration, or itinerary deviation rates between modeled and observed values (Ross, 2011). Discrepancies between observed and simulated distribution of trailhead-of-origin were also small. For season-total intended use across all zones, the modeled 95% prediction interval was 103,941 ±1,742 visitor nights, and the observed intended use from the park's permit database was 105,515 visitor nights. Because the observed intended use fell within the prediction interval, we concluded no significant difference between modeled and observed values. For use at the zone-night level, we performed the same type of analysis, adjusted for multiple comparisons over all 8,109 zone-nights (53 zones x 153 nights). At 95% confidence for each zone-night, we expect observed zone-night use to fall outside the 95% prediction interval in 5% of the zone-nights. Observed intended use fell outside of the modeled 95% prediction interval in less than 1% of all zone-night combinations, indicating that there was no significant difference in zone-night use between the model and permit database. Therefore, we concluded that the dynamic model accurately simulated intended visitor behavior.

Deviation Satistics Obtained from the Visitor Survey

Based on the 1,123 usable visitor surveys, mean intended trip duration was 2.71 days (SD = 1.69), whereas actual trip duration was 2.35 days (SD = 1.45). The surveyed parties shortened trips by as many as 11 days and lengthened them by as many as 9 days. Among the parties that deviated temporally, the mean temporal deviation was -1.02 days (SD = 1.45). Trips were shortened at a rate of 0.42 nights per night the party intended to spend in the wilderness, and this rate was not significantly different than the value of 0.33 estimated in the 1970s (van Wagtendonk & Benedict, 1980).

Linear regression showed that actual trip duration did not depend significantly on trip start date ($P = 0.786$), but it increased significantly with increasing party size (0.043 days per additional party member, $P = 0.000276$) and longer intended trip duration (0.695 days per additional day of intended duration, $P < 0.001$). That is, actual trip duration was longer for larger parties and those that intended to take long trips to begin with. When applied to the population of all parties in the permit database, the regression equation predicted a mean actual trip length of 2.12 nights, significantly lower than the intended mean trip duration of 2.48 nights. Thus, in the temporal deviation algorithm, we increased exit probabilities in the transition matrix so that the model produced a mean trip duration of 2.12 nights.

In 2010, 36.2% of all parties deviated temporally from their intended itineraries, and 54.4% deviated spatially; 25.2% of all parties deviated both spatially and temporally. Spatial and temporal deviations were not independent of one another ($\chi^2 = 70.9$, $df = 1$, $P < 0.001$). Parties had a tendency to either deviate both spatially and temporally or to not deviate at all. Survey results showed that parties that deviated spatially were more likely to deviate early in their trip than later; 30.6% of survey respondents spent their first night in a different zone than intended, 17.2% first deviated from intended spatial distribution on the second zone visited, and 6.5% first deviated from intended spatial distribution after their second zone transition.

Model-Predicted Effect of Itinerary Deviation

Prior to application of the deviation algorithm, model-predicted season-total use and 95% prediction interval from trips originating in Yosemite was 103,941 ± 1,742 visitor nights (Table 1). Applying the effect of itinerary deviation in the model reduced predicted season-total use to 89,997 ± 1,743, and this reduction was statistically significant ($t = -163.66$; $df = 1947$; $P < 0.001$). Use of the Yosemite Wilderness originating outside of the park accounted for an average of 10,010 additional visitor nights per season and had very little effect on capacity exceedance probabilities (Table 1).

Effect of Management Scenarios on Use Levels and Trailhead Relationships

Figure 4 displays zone capacity exceedance probabilities graphically; the shading of each cell in the graphical array indicates the model-predicted probability that the capacity of a particular zone will be exceeded on each night of the season. Darker shading indicates a higher probability of capacity exceedance. Under the current-use scenario, high probabilities of use exceeding capacity were limited to five zones (63, 66, 67, 75, 81), as indicated by the five rows in the top panel of Figure 4 that contain the largest number of dark cells. For example, predicted use in zone 75 (Figure 3) had a nonzero probability of exceeding capacity on every night from June 13 to September 29 (Figure 4). Out of the 8109 zone-nights, there were 126 zone-nights, all in zones 66, 67, 75 and 81, that had more than a 30% probability of exceeding capacity (Table 1). Use was predicted to exceed capacity only rarely in the remainder of the 53 wilderness zones (top panel of Figure 4).

The relationship between trailhead-of-origin and zone use (Figure 5) is expressed as the fraction of total use in each wilderness zone (row) that is due to parties that originate their trip at a given trailhead (column). Darker cells indicate higher fractions of use originating from the given trailhead. With the exception of only two zones (other than three zones in which no camping is allowed), each wilderness zone received at least 20% of its overnight use from one trailhead, under current conditions. Two of the four most highly used zones received a majority of their use from one trailhead. For example, 54% of the total visitor-nights in zone 75 received originated from trailhead 36 (Figures 3 and 5).

The maximum-allowed-use scenario produced a mean use level of 2,260 visitors per night in the Yosemite wilderness. The nightly capacity of the 53 wilderness zones sums to 4,200 visitors. Thus, even when all of the *trailhead quotas* are filled, total use is only 54% of the allowable *wilderness zone capacity*. However, even though trailhead use in this scenario was given only by quota and not affected by visitor preference, spatial use was not uniformly distributed across the zones, resulting in exceedance of zone capacity every

night in many zones (Figure 4). On the other hand, predominant travel patterns are such that, despite maximum-use conditions as allowed by the trailhead quotas, simulated visitor use in many zones rarely, if ever, exceeded capacity. For example, once the model reached equilibrium (fourth day of the simulation), use in zone 75 (Figure 3) had over a 90% chance of exceeding capacity every night, whereas the probability of use exceeding capacity in zone 59 (Figure 3) was less than 0.2% on any given night.

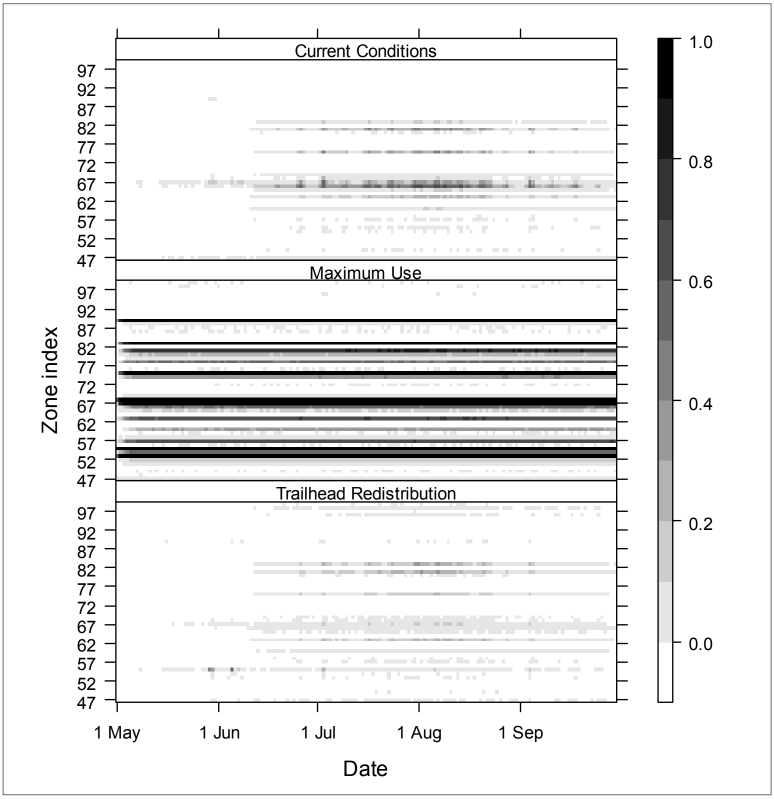

Figure 4. Mean probability of overnight wilderness visitor use exceeding capacity, based on 1,000 simulations, for current-condition, maximum-allowed-use, and redistribution scenarios. The vertical axis refers to the 53 Yosemite wilderness zones, each of which is represented by a horizontal bar. Each of the 53 horizontal bars contains 153 cells representing the 153 nights from May 1 to Sept. 30. The darker the cell, the higher the probability that the zone exceeds its stated visitor capacity for that night. No camping is allowed in zones 70, 73, and 82; hence those zones received no use in simulations.

The zone use-trailhead relationship generated by this scenario was somewhat different than that under current conditions (Figure 5) because larger fractions of use in the maximum-allowed-use scenario originated from trailheads that are currently lightly used, resulting in a more uniform distribution of zone use across trailheads. However, the similarities in the top two panels of Figure 5 show that that regardless of how heavily or lightly used a trailhead is, certain trailheads are always the primary contributors to use in certain zones, reflecting the inherent geography of the wilderness and the behavior and

physical abilities of users. For example, under current conditions, 54% of the total use in zone 75 was from parties that originated their trip at trailhead 36, and this fraction remained unchanged under the maximum-allowed-use scenario. This is due to the proximity of zone 75 to trailhead 36 (Figure 3), regardless of whether use of trailhead 36 is given by current visitor preference or is artificially filled to quota every day.

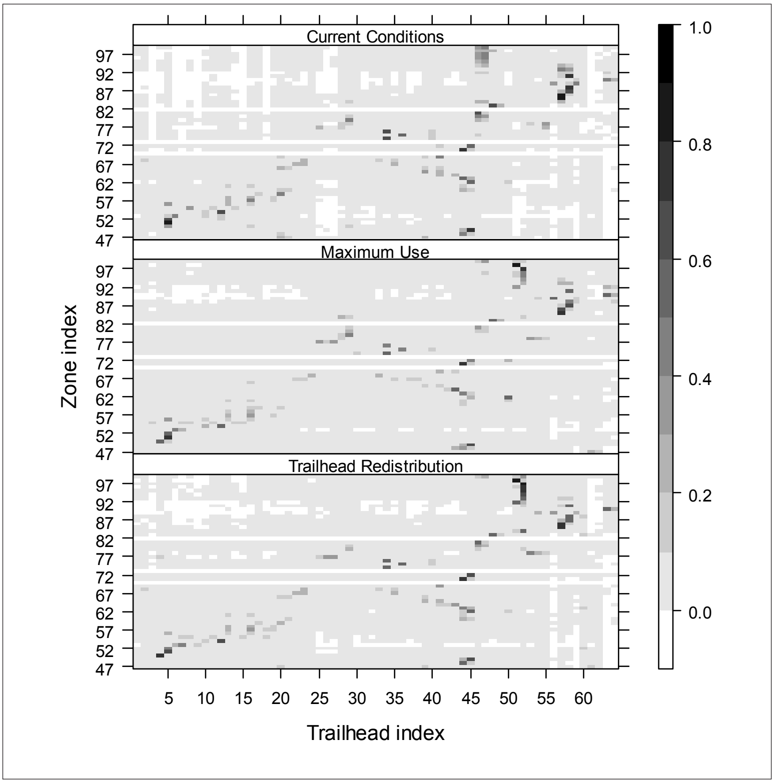

Figure 5. Individual trailhead contribution to wilderness zone overnight visitor use for current-condition, maximum-allowed-use, and redistribution scenarios. The vertical axis refers to the 53 Yosemite wilderness zones, and the horizontal axis refers to the 64 Yosemite Park trailheads. Shading indicates the fraction of season-total use in each zone originating at each trailhead. No camping is allowed in zones 70, 73, and 82; hence those zones received no use in simulations.

The redistribution scenario was successful in lowering probabilities of capacity exceedance in the most heavily used zones, while accommodating the current level and temporal distribution of use (Figure 4). Under the redistribution scenario, mean visitor use exceeded capacity on zero nights, and use on only eight out of 8,109 possible zone-nights had more than a 30% probability of exceeding capacity (Table 1). For example, under current conditions, use in zone 75 (Figure 3) had at least a 30% chance of exceeding capacity on 15 nights during the season, whereas under the redistribution scenario, there were no nights on which the probability of use exceeding capacity in zone 75 was greater than 30%. To achieve these results, 3,575 parties per year, on average, were redistributed to less heavily used parts of the park. This represented spatial redistribution of over 22,000 visitor nights (about 25% of total use originating in Yosemite) from heavy- to low-use

areas. This redistribution increased the probability of capacity exceedance in zones that are currently lightly used, although the probabilities of exceedance in these zones on any given night were generally less than 10% (Figure 4). For example, use in zone 98 had no probability of exceeding capacity on any night under current conditions, whereas under the redistribution scenario, there was a nonzero probability of use exceeding capacity on 88 different nights. However, the maximum probability of capacity exceedance across all of these nights was 9.6%. The zone use-trailhead relationship for this scenario was very similar to that for the maximum-use scenario (Figure 5), providing more evidence that the dependence of zone use on trailhead-of-origin is determined primarily by the park's geography and not by how parties are distributed among the trailheads. For example, under both current conditions and maximum allowed use, zone 75 received 54% of its total use from parties that originated at trailhead 36 (Figure 3). Under the redistribution scenario, this fraction was reduced only slightly, to 53%, again reflecting the fact that zone 75 is adjacent to trailhead 36.

Discussion

Model Characteristics and Performance

We created and validated a model of wilderness use that reproduced observed use characteristics at the zone-night resolution with a minimal set of assumptions. Validation showed that averaged over many simulations, the model produced the same intended wilderness trip characteristics as those observed. This result indicated the efficacy of our approach to modeling trip duration dynamically with transition probabilities rather than by predetermining trip duration for each party at the beginning of its trip. The transition matrix approach also avoided having to limit itineraries to a finite set. Observed, intended use calculated from the permit database did not differ statistically from that predicted by the model at either the season-total or zone-night level, indicating that any small differences in trip characteristics that may exist between the simulation model and the permit database did not affect the spatiotemporal distribution of wilderness use.

We emphasize the dynamic nature of trip simulations in our model. The only trip characteristics that are statically assigned to a simulated party at the beginning of its trip are start date, party size, and trailhead, all according to the actual distributions of those attributes from the permit database. Trailhead assignment was somewhat dynamic in the sense that if a party's selected trailhead was at quota on that day, a new trailhead was selected from the remaining trailheads available on that day. The end user of the model can easily adjust the trailhead quotas and the number of parties that start on each day of the season to investigate other scenarios and examine the effects of increasing or decreasing particular trailhead quotas on use. Itinerary and trip duration were determined dynamically as the party traveled, based on probabilities of state transition and effects of spatial and temporal deviation. Thus, camping locations and trip duration of each simulated party were not known until the party completed its simulated trip.

By using probabilistic travel zone transition matrices we neither specified trip durations at the start of a trip nor limited the possible routes taken by parties. This means that any feasible trip that can occur in Yosemite has a possibility of occurring in the model. Since Yosemite is such a large and interconnected area, creating "typical" itineraries would be difficult and would not accurately reflect the full picture of use in the park.

The model accounts for spatial deviation dynamically. Unlike temporal deviation, spatial deviation is defined categorically, so there is no way to measure its effects by an average of some quantity. Accounting for spatial deviation in the model allows simulation of crucial information that is not available otherwise. Standard statistical analysis may tell us how many parties deviate, but not what effect it has on overall wilderness visitor use. The only way to see the effects of spatial deviation in the park is to simulate it. By not using preselected routes or durations, we were able to dynamically alter routes to represent deviation.

We also emphasize that the model is not a "black box" simulation containing numerous parameters whose values have been chosen through a calibration procedure to minimize differences between model-predicted and observed use. The parameter governing increase in exit probability was the only model parameter whose value was determined through a calibration procedure, and it was calibrated by matching simulated and observed mean trip duration. No parameterization was performed by attempting to match model-predicted and observed wilderness use; instead, model validation was used to show that our modeling approach yields use values consistent with those observed. Thus, our model framework is not specific to Yosemite but has broad applicability.

Itinerary Deviation and Effects on Use Patterns

As expected, visitors deviated both spatially and temporally from intended trip itineraries. Based on the survey sample, 66% of parties deviated from their intended itinerary, compared with 62% reported for Yosemite wilderness users in the 1970s (van Wagtendonk & Benedict, 1980), and this difference was not significant (z = 1.71, P = 0.087). However, the distribution of deviation types differed significantly between the 1970s and the current study (χ^2 = 28.7, df = 3, P < 0.001); a smaller proportion of parties reported some sort of temporal deviation in 2010 (35.5% versus 41.5%), and a larger proportion of parties reported some sort of spatial deviation in 2010 (56.4% versus 49.2%). Mean temporal deviation in this study was -1.02 days, compared with values observed in the 1970s of -0.58 days in Yosemite (van Wagtendonk & Benedict, 1980) and -0.60 days in Sequoia and Kings Canyon national parks further south in the Sierra Nevada (Parsons et al., 1982).

Our model predicted that season-total use would be overestimated by about 15% without accounting for the difference between intended and actual trip duration (Table 1), compared with 23% estimated for Sequoia and Kings Canyon by Parsons et al. (1982). Itinerary deviations resulted in a lower fractional discrepancy between intended and actual use in our study because mean party size was smaller (2.9 versus 3.3 visitors per party), mean actual trip duration was smaller (2.1 nights versus 4.5 nights), and the fraction of parties reporting temporal deviation was smaller (35.5% versus 44.7%) in our study than in that of Parsons et al. (1982). Similarly, mean party size and trip duration of Yosemite wilderness parties in the 1970s were smaller than we observed by 0.34 visitors per party and 0.46 nights per trip, respectively (van Wagtendonk & Benedict, 1980). In general, smaller party sizes, shorter intended trip durations, and decreased probability of temporal deviation decrease the relative difference between use estimates made from intended trip itineraries and those made from actual itineraries, but the 15% discrepancy we estimate in overall use is still substantial from a management standpoint.

Visitor management systems that use trailhead quotas rather than wilderness zone or campsite-specific quotas are designed, in part, to allow visitors the freedom to roam and to give visitors the right to alter their plans serendipitously. Such systems can maximize freedom to visitors once inside the wilderness, consistent with wilderness experience and resource constraints (van Wagtendonk & Coho, 1986). This may increase the potential of a wilderness to provide visitors with a sense of inspiration, escape, and/or autonomy. This study confirmed that visitors are altering their trips (i.e., deviating from their intended trip itineraries) in both time and space, thereby demonstrating both the necessity for managers to allow, and proof of visitors exercising those rights to, itinerary freedom. However, the frequency with which wilderness zone use exceeded nightly capacity was much lower when the effects of deviation were incorporated. Thus management actions to lower visitor use of certain zones, if informed by permit data without accounting for itinerary deviations, are likely to be overly conservative.

Although shorter trip durations do not necessarily lead to zone capacities being exceeded, they do lead to a greater fraction of total use in zones that are readily accessible from trailheads. Three such travel zones that are among the eight most heavily used zones today were not in the top eight in the 1970s, providing some evidence that a preference for shorter trips may be leading to increased use in zones close to trailheads. Redistributing some of these shorter trips to parts of the park that receive less use could lower the probability of exceeding zone capacities under current use levels and trip characteristics.

Use Scenarios and Zone-trailhead Relationships

The current-use scenario demonstrates the model's use as a tool to monitor current conditions. This scenario accounts for itinerary deviation and can also include USFS trailhead contribution to produce our best estimate of actual spatiotemporal distribution of wilderness visitor use in 2010. The redistribution scenario showed how the model can be used as a predictive tool to test various management scenarios. Our redistribution trailhead quota solution illustrates just one of many ways in which current use can be redistributed to lower-use areas in the park to achieve substantially lower probabilities of exceeding zone capacities, without changing overall amount of use, temporal distribution of use, or any other party or trip attribute. By lowering trailhead quotas at nine of the most popular trailheads, and redistributing an average of 3,575 parties annually from those trailheads to less popular trailheads, we simulated a condition in which the current level of use is still accommodated, but the probability that use would exceed zone capacities was greater than 30% in only eight out of 8,109 possible zone-nights, compared with 126 zone-nights under current conditions. This suggests that trailhead quotas can be a viable approach to managing visitor use in wilderness.

The maximum-allowed-use scenario shows the model can be used in a more experimental sense, testing conditions that may not be truly feasible but that still may provide insight into the system. It allowed us to calculate the system's inherent zone use-trailhead relationship, unconfounded by visitor preference for particular trailheads. Had we selected trip itineraries from a fixed set, no matter how large, the model would not have retained the full complexity of this relationship.

We found that on some nights, some wilderness zones likely receive a level of use that exceeds their stated overnight capacities. We produced a tool that allows managers to accurately determine trailhead quotas that bring visitor use levels in overused zones back down to capacity, while still accommodating the same overall amount of wilderness visitor use. It is ultimately up to managers to decide how best to use the modeling tool provided, but it may be worth noting that a previous study using stated-choice modeling found Yosemite visitors would be willing to accept a lower chance of receiving a permit in order to gain improvements in other conditions, such as having fewer encounters with other visitors during their trips (Newman, Manning, Dennis, & McKonly, 2005).

Under current visitor use levels and spatiotemporal distribution, most wilderness travel zones receive the majority of their use from only a few trailheads; 18 of the 53 zones receive over 50% of their use from one trailhead. Only a relatively small part of this observed zone use-trailhead relationship is determined by visitor preference in time and space. The similarity in the relationship between zone use and trailhead of origin across the three scenarios (Figure 5) shows that there is an inherent relationship between zone use and trailhead of origin that is determined by the geography of the park, and the physical capabilities and behaviors of wilderness users in selecting routes and camping locations. The simulations showed that even after removing the effect of visitor preference for trailheads or redistributing visitors to less popular trailheads, certain trailheads are still the primary source of use in particular zones.

Filling every trailhead's quota on every day under the *maximum allowed use* scenario resulted in visitor use that totaled only 54% of the sum total of the wilderness zone capacities. This might suggest a disconnect between the trailhead quotas and the wilderness capacity, calling into question the trailhead quotas as a viable basis for managing visitor use of the wilderness. However, allowing visitors the freedom and autonomy to decide where to camp makes it impossible to perfectly match these two measures. Most of the unused capacity is in remote areas of the park that receive little use. The quotas for the trailheads that serve those zones could be increased, but that would not translate into higher use in those "underused" portions of the park; it likely would only create additional overcapacity issues in the zones closer to those trailheads.

Requiring overnight users to camp in designated campsites or in predetermined wilderness travel zones, and/or to adhere to fixed itineraries without the freedom or

flexibility to modify their trip spatially or temporally to adapt to changing conditions or desires, would achieve a more predictable spatiotemporal use distribution across the wilderness landscape. This could help reduce use impacts at popular locations, maximizing the naturalness and undeveloped values of wilderness called for in the Wilderness Act. The trade-off, however, is a diminished sense of the "outstanding opportunities for solitude or a primitive and unconfined recreation" also called for by the Wilderness Act. Although trailhead quotas are a regulatory action, they are applied to visitors prior to entering the wilderness, thus preserving to a greater degree the autonomy and "unconfined recreation" many wilderness visitors seek. The increased understanding and predictability of visitor use patterns afforded by a computer simulation model may make trailhead quotas an effective and reasonable compromise between the sometimes competing values of regulation to maximize resource protection on the one hand, and preserving visitor freedom and autonomy on the other.

Management Implications

We conclude that the inherent relationship between wilderness travel zone use and trailhead use has changed very little since the inception of the quota system in Yosemite, given that this relationship is based primarily on geography, behavior and physical capabilities of wilderness users, and the quotas themselves. Thus, the original quota system remains a viable basis from which to determine future management. More importantly, our redistribution scenario illustrates that some portion of the current visitor use could be redistributed to less popular areas in the park to achieve substantially lower probabilities of exceeding zone capacities, without changing overall amount of use, temporal distribution of use, or any other party or trip attribute.

However, it is difficult to confidently predict how visitors seeking permits would react to reduced permit availability at popular trailheads. Quotas could be increased at other trailheads to allow for the same total amount of wilderness access, but those other trailheads are clearly not as popular with visitors. Would visitors accept a less preferred trailhead, one that likely would not lead to their desired destination? Would they decline to take a wilderness trip at all if they could not gain access via their preferred trailhead?

On the other hand, this is not fundamentally different than the system that is now in place. Visitor use currently is being redistributed, relative to spatial demand, by way of the trailhead quotas. The most popular trailheads in Yosemite have daily quotas that are certainly lower than the demand for permits for those trailheads. Wilderness visitors very commonly end up choosing trailheads that are not their first choice when they see the "Trailhead Full" sign on the list of trailheads in the Wilderness Centers where they obtain their permits. In this sense, our redistribution scenario is simply an extension of the current management strategy.

Another possible outcome of significantly reducing use at some popular trailheads is that visitor use could increase in other portions of the wilderness that are currently more lightly used. This could increase visitor use impacts to resources in those more pristine portions of the wilderness, as well as decrease opportunities for solitude, and in the long term could narrow the range of conditions and opportunities available in the wilderness (Cole, 2001). Before any attempt is made to redistribute use, managers would want to think very carefully about which low-use portions of a wilderness are truly underused, in the sense that they could accommodate more visitor use without unacceptable consequences, and which portions are low-use by design (i.e. by management objective) and should remain as low-use areas.

A product of simulation modeling such as ours is that managers have a more accurate, and more quantitative, understanding of existing conditions. The vastness of the wilderness, and its many access points, limits the ability of managers to precisely monitor visitor use conditions, particularly the number of visitors camped overnight in any given wilderness zone. A simulation model can generate reliable estimates of these hard-to-measure variables, providing managers information about current use conditions to inform establishment of a baseline of wilderness character. The spatiotemporal model outputs

allow managers to identify the place and time that use occurs, especially when and where there is concern that concentrated use could lead to conflicts among different user types or impacts to fragile ecological resources or wildlife habitat (Lawson et al., 2006). Other model scenarios can provide sideboards to facilitate the prescriptive process of selecting management alternatives. With such a model, managers can evaluate the effectiveness of alternative management strategies (e.g. alternative trailhead quotas) more efficiently and with less risk than with trial and error, and can evaluate potential increased or decreased visitor use demands and develop informed plans to prepare for those potential conditions (Lawson et al., 2006).

Limits on visitor use may be needed when demand is very high and other management tools alone are inadequate to protect resource and experiential conditions. Trailhead quotas may be an effective externally-applied management tool that allows for more visitor autonomy once in the wilderness. For trailhead quotas to be effective, however, managers must have a very good understanding of the relationship between the trailhead of origin of trips, and the resulting spatiotemporal distribution of users. By incorporating novel approaches to simulating visitor itineraries dynamically and modeling observed tendencies for visitors to deviate from intended itineraries, we have developed a simulation model capable of quantifying the dependence of wilderness zone use on trailhead of origin, which is the key piece of information necessary for managers to successfully apply a trailhead quota system. Simulation results show that in a large, complex, and heavily used wilderness such as Yosemite, adjustment of trailhead quotas can be a frontcountry management tool that is effective in achieving backcountry management objectives. In any wilderness setting, there will always be certain destinations that are more popular than others; our modeling approach allows managers to quantify the degree to which management objectives can be met by redistributing use away from popular areas and towards less heavily used areas.

However, to enhance the utility of any model, it is advisable that managers seek more information about how visitors select trailheads and how they respond to full quotas. While our model simulates how visitors behave once assigned to a trailhead, it would be improved if we learned more about why visitors choose certain trailheads and travel itineraries. With such information, managers could make more informed choices when evaluating different visitor use scenarios to simulate with the model, and could improve their own decision-making processes when choosing between education or regulation strategies for wilderness management.

References

Bishop, I. D., & Gimblett, H. R. (2000). Management of recreational areas: GIS, autonomous agents, and virtual reality. *Environment and Planning B: Planning and Design*, 27, 423–435.

Cole, D. (2001). Balancing freedom and protection in wilderness recreation use. *International Journal of Wilderness*, 7(1), 12–13.

Cole, D. (2009). Ecological Impacts of Wilderness Recreation and Their Management. In C. Dawson & J. Hendee, *Wilderness management: Stewardship and protection of resources and values* (4th ed., pp. 396–407). Golden, CO: Fulcrum.

Cole, D., Cahill, K., & Hof, M. (2005). Why model recreation use? In D. N. Cole (comp.), *Computer simulation modeling of recreation use: current status, case studies, and future directions*. Gen. Tech. Rep. RMRS-GTR-143. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Cole, D., & Daniel, T. (2003). The science of visitor management in parks and protected areas: from verbal reports to simulation models. *Journal for Nature Conservation,* 11, 269–277.

Dawson, C., & Hendee, J. (2009). *Wilderness management: Stewardship and protection of resources and values* (4th ed.). Golden, CO: Fulcrum.

Douglas, M. (2011). *Yosemite wilderness visitor travel patterns: Implications for trailhead permit quotas.* MS Thesis, Arcata, CA: Humboldt State University.

Gimblett, H. R., Richards, M. T., & Itami, R. M. (2001). RBSim: Geographic simulation of wilderness behavior. *Journal of Forestry*, 99(4), 36–42.
Hammitt, W., & Cole, D. (1998). *Wildland recreation: Ecology and management* (2nd ed.). Wiley & Sons.
Imagine That Inc. (2010). ExtendSim 8 software. San Jose, CA: Imagine That Inc.
Itami, R., Raulings, R., MacLaren, G., Hirst, K., Gimblett, R., Zanon, D., & Chladek, P. (2003). RBSim 2: simulating the complex interactions between human movement and the outdoor recreation environment. *Journal for Nature Conservation*, 11:278–286.
Lawson, S., Manning, R., Valliere, W., & Wang, B. (2003). Proactive monitoring and adaptive management of social carrying capacity in Arches National Park: An application of computer simulation modeling. *Journal of Environmental Management*, 68:305–313.
Lawson, S., Kiely, A., & Manning, R. (2004). *Computer simulation as a tool for developing alternatives for managing crowding at wilderness campsites on Isle Royale.* Working Papers of the Finnish Forest Research Institute, 2:114–119. Http://www.metla.fi/julkaisut/workingpapers/2004/mwp002.htm.
Lawson, S., Itami, R., Gimblett, H., & Manning, R. (2006). Benefits and challenges of computer simulation modeling of backcountry recreation use in the Desolation Lake Area of the John Muir Wilderness. *Journal of Leisure Research*, 38, 187–207.
Leung, Y., & Marion, J. (2000). Recreation impacts and management in wilderness: A state-of-knowledge review. In D. Cole, S. McCool, B. Borrie, & J. O'Laughlin (Comps.), *Wilderness science in a time of change conference—Volume 5: Wilderness ecosystems, threats, and management*; 1999 May 23–27; Missoula, MT. Proceedings RMRS-P-15-VOL-5. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
Manning, R., & Lime, D. (2000). Defining and managing the quality of wilderness recreation experiences. In D. Cole, S. McCool, B. Borrie, & J. O'Laughlin (Comps.), *Wilderness science in a time of change conference—Volume 4: Wilderness visitors, experiences, and visitor management*; 1999 May 23–27; Missoula, MT. Proceedings RMRS-P-15-VOL-4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
Monz, C., Cole, D., Leung, F., & Marion, J. (2010). Sustaining visitor use in protected areas: Future opportunities in recreation ecology research based on the USA experience. *Environmental Management*, *45*, 551–562.
Newman, P., Manning, R., Dennis, D., & McKonly, W. (2005). Informing carrying capacity decision making in Yosemite National Park, USA using stated choice modeling. *Journal of Park and Recreation Administration*, 23, 75–89.
Parsons, D. P., Stohlgren, T. J., & Kraushaar, J. M. (1982). Wilderness permit accuracy: Differences between reported and actual use. *Environmental Management*, *6*, 329–335.
Potter III, F. I., & Manning, R. E. (1984). Application of the wilderness travel simulation model to the Appalachian Trail in Vermont. *Environmental Management*, 8, 543–550.
Ross, K. (2011). A simulation model for wilderness use in Yosemite National Park. M.S. Thesis, Arcata, CA: Humboldt State University.
Schecter, M., & Lucas, R. (1978). *Simulation of recreational use for park and wilderness management*. Baltimore, MD: Johns Hopkins University Press.
Schumaker, N. H., Brookes, A., Dunk, J. R., Woodbridge, B., Heinrichs, J. A., Lawler, J. J., Carroll, C., & LaPlante, D. (2014) Mapping sources, sinks, and connectivity using a simulation model of northern spotted owls. *Landscape Ecology*, DOI 10.1007/s10980-014-0004-4.
Smith, V., & Krutilla, J. (1976). *Structure and properties of a wilderness travel simulator: An application to the Spanish Peaks Area*. Johns Hopkins University Press, Baltimore.
Underhill, A. H., Xaba, A. B., & Borkan, R. E. (1986). The wilderness use simulation model applied to Colorado River boating in Grand Canyon National Park, USA. *Environmental Management*, 10, 367–374.

van Wagtendonk, J. W. (1978). Using wilderness permits to obtain route information. In M. Shechter & R.C. Lucas (Eds.), *Simulation of recreational use for park and wilderness management* (Appendix I, pp. 197–203). , Baltimore, MD: Johns Hopkins University Press.

van Wagtendonk, J. W. (1981). The effect of use limits on backcountry visitation trends in Yosemite National Park. *Leisure Sciences*, 4, 311–323.

van Wagtendonk, J. W. (1986). The determination of carrying capacities for the Yosemite Wilderness. In R. C. Lucas (comp.), *Proceedings of the National Wilderness Research Conference*, General Technical Report INT-212, U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, pp. 456–461.

van Wagtendonk, J. W. (2003). The wilderness simulation model: A historical perspective. *International Journal of Wilderness*, 9(2), 9–13.

van Wagtendonk, J. W. (2004). Simulation modeling of visitor flows: Where have we been and where are we going? Working Papers of the Finnish Forest Research Institute, 2:127–134. Retrieved from http://www.metla.fi/julkaisut/workingpapers/2004/mwp002-19.pdf

van Wagtendonk, J. W., & Benedict, J. M. (1980). Wilderness permit compliance and validity. *Journal of Forestry*, *78*, 399–401.

van Wagtendonk, J., & Coho, P. (1986). Trailhead quotas: Rationing use to keep wilderness wild. *Journal of Forestry*, 84, 22–24.

Wang, B., & Manning, R. E. (1999). Computer simulation modeling for recreation management: A study on carriage road use in Acadia National Park, Maine, USA. *Environmental Management*, 23, 193–203.