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Assessing Impacts of Roads: Application of a Standard Assessment Protocol

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Abstract

Adaptive management of road networks depends on timely data that accurately reflect the impacts those systems are having on ecosystem processes and associated services. In the absence of reliable data, land managers are left with little more than observations and perceptions to support management decisions of road-associated disturbances. Roads can negatively impact the soil, hydrologic, plant, and animal processes on which virtually all ecosystem services depend. The Interpreting Indicators of Rangeland Health (IIRH) protocol is a qualitative method that has been demonstrated to be effective in characterizing impacts of roads. The goal of this study were to develop, describe, and test an approach for using IIRH to systematically evaluate road impacts across large, diverse arid and semiarid landscapes. We developed a stratified random sampling approach to plot selection based on ecological potential, road inventory data, and image interpretation of road impacts. The test application on a semiarid landscape in southern New Mexico, United States, demonstrates that the approach developed is sensitive to road impacts across a broad range of ecological sites but that not all the types of stratification were useful. Ecological site and road inventory strata accounted for significant variability in the functioning of ecological processes but stratification based on apparent impact did not. Analysis of the repeatability of IIRH applied to road plots indicates that the method is repeatable but consensus evaluations based on multiple observers should be used to minimize risk of bias. Landscape-scale analysis of impacts by roads of contrasting designs (maintained dirt or gravel roads vs. non- or infrequently maintained roads) suggests that future travel management plans for the study area should consider concentrating traffic on fewer roads that are well designed and maintained. Application of the approach by land managers will likely provide important insights into minimizing impacts of road networks on key ecosystem services.

Key Words: adaptive management, assessment, monitoring, off-highway vehicles, oil and gas, rangeland health

INTRODUCTION

Adaptive management decision processes depend on timely data that accurately reflect the impacts of management decisions (both action and inaction) on ecosystem processes and associated services. One of the more pressing rangeland management concerns in arid and semiarid lands globally is the proliferation of roads, off-highway vehicles, utility transmission lines, power generation, and other infrastructure- and transportation-associated disturbances (Okayasu et al. 2007; Watts et al. 2007; Leu et al. 2008; Walston et al. 2009; Leinwand et al. 2010; Keshkamat et al. 2012). However, there are relatively few cost-effective methods for detecting the effects of such disturbance activity on soils, vegetation, and hydrology. In the absence of reliable data, land management agencies and private land owners are left with little more than observations and perceptions to support management decisions of road networks, energy development, and vehicle-based recreational activities (hereafter referred to as roads). An emotional debate is growing in the absence of systematic, evidence-based decisions, particularly for off-road vehicle traffic (e.g., Wuerthner 2007; Hawthorne 2009), which results in the creation or persistence of thousands of kilometers of tracks in arid and semiarid regions throughout the world.

Roads can negatively impact the soil, hydrologic, plant, and animal processes on which virtually all ecosystem services depend (Webb and Wilshire 1983; Duniway and Herrick 2011). Research indicates many of the negative impacts of these disturbances on soils and vegetation in rangeland ecosystems are caused by alteration of surface hydrologic and erosional processes (Thurow et al. 1993; Belnap and Gillette 1997; Webb 2002). However, these processes are difficult and time intensive to measure quantitatively.

The Interpreting Indicators of Rangeland Health (IIRH) protocol is a qualitative method that describes the status of hydrologic and erosional processes in these ecosystems (Pellant et al. 2005) and has been demonstrated to be effective in characterizing impacts of roads (Duniway et al. 2010). IIRH was developed by a US interagency group in the late 1990s, drawing on literature and experiences from around the world. IIRH is based on the ecological site concept (Herrick et al. 2006) in combination with expert knowledge of soil and vegetation processes in a conceptual reference state. The current version of IIRH (Version 4; Pyke et al. 2002; Pellant et al. 2005) requires the development of ecological site-specific "reference sheets" which provide a consistent reference for all evaluations of land on a particular group of soils (in the United

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Table 1. IIRH indicator numbers (no.), description, attributes with which indicators are associated (Pellant et al. 2005), and Friedman's test results comparing the mean distribution of the indicator departure ratings.

Indicators		Attribute[1]				Within road strata		
No.	Description	SSS	HF	BI	Road vs. nonroad[2]	Type[4]	Impact[3]	ES group[5]
1	Number and extent of rills	●	●		**	**		
2	Presence of water flow patterns	●	●		**			
3	Number and height of erosional pedestals or terracettes	●	●					*
4	Bare ground	●	●		**		**	
5	Number of gullies and erosion associated with gullies	●	●			*	**	
6	Extent of wind scoured, blowouts and/or depositional areas	●						**
7	Amount of litter movement	●			**	**		
8	Soil surface (top few mm) resistance to erosion	●	●	●		**		
9	Soil surface structure and SOM content	●	●	●	**		*	
10	Effect of plant community composition and spatial distribution on infiltration and runoff		●					**
11	Presence and thickness of compaction layer	●	●	●	**		**	**
12	Functional/structural groups			●				**
13	Amount of plant mortality and decadence			●				**
14	Average percent litter cover		●	●				
15	Expected annual production			●	*			*
16	Potential invasive (including noxious) species (native and non-native)			●				**
17	Perennial plant reproductive capability			●				

[1] SSS, Soil and Site Stability; HF, Hydrologic Function; BI, Biotic Integrity.
[2] Blocking on ES group, $n=70$.
[3] High- vs. low-impact road plots, blocking on road type and ES group, $n=80$.
[4] Major vs. Minor road plots, blocking on impact and ES group, $n=80$.
[5] Blocking on road type (including nonroad); $n=110$.
*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.

States) or group of soils with production potential and response to management (globally). In the IIRH technique, each user evaluates the relative departure of 17 indicators (see Table 1 for list and brief description) of rangeland health against a description of the reference range of variation for each indicator using a five-category qualitative scale (none-to-slight, slight-to-moderate, moderate, moderate-to-extreme, or extreme-to-total). Once all indicators have been evaluated, three attributes of rangeland health (Soil and Site Stability, Hydrologic Function, and Biotic Integrity) are evaluated by synthesizing the five-category scale of departure ratings for the relevant indicators for each attribute using a "preponderance of evidence" approach (Pellant et al. 2005), taking into account both the relative importance of each indicator for the particular ecological site, and confidence in evaluating the indicator. In a typical application of the protocol, an evaluation area of 0.1–5 ha is selected, the ecological site is determined, and the area is traversed by all observers, noting the status of each of the 17 indicators relative to the conditions described in the reference sheet. The observers conduct assessments individually and then use a consensus process to arrive at a final rating. This process may require revisiting parts of the evaluation area to review observations.

The IIRH technique is particularly useful for adaptive management because it can provide relatively rapid assessments of a wide range of ecological processes that are necessary for understanding proximity to ecological thresholds (Bestelmeyer 2006). This approach of evaluating the current condition of a site against the site's potential facilitates the evaluation of impacts of road development and use across areas with varying potential to conserve soils, store and release water, and produce kinds and amounts of vegetation. IIRH is widely applied by two of the three US agencies responsible for assessment and monitoring of the majority of the nation's rangelands (Natural Resource Conservation Service [NRCS] and Bureau of Land Management [BLM]).

With an appropriate and statistically robust sampling design, IIRH plot assessments done across a landscape can provide information on how resilience (Gunderson 2000) and restoration potential varies across different soil-geomorphic units and vegetation communities (King and Hobb 2006; Miller 2008; Herrick et al. 2010). In heterogeneous landscapes, great gains in sampling efficiency and power to detect change can be achieved through a stratified sampling design that incorporates a priori understanding of factors that account for landscape variability in ecological processes (Elzinga et al. 2001) due to differences in potential (e.g., ecological sites), disturbance (e.g., roads), and management (e.g., ownership). Additionally, an approach to stratification that includes known, nonzero sampling probabilities for all land within the area of interest helps ensure that sufficient evaluations are completed in areas of management concern (e.g., near roads), the information is scalable, and results can be combined with data from studies in the same or different areas using comparable methods.

To assess how roads are impacting rangeland health, it is necessary to compare assessments done in areas where road impacts are of concern to areas with similar soils and management but not impacted by roads. Thus, a logical sampling design for detecting road impacts with IIRH would include stratification by ecological site (using existing NRCS soil surveys to map ecological sites), management units (e.g., grazing allotments), and proximity to roads (using route inventory data). The magnitude of direct and indirect impacts of roads on ecosystem processes often varies with road design or lack thereof (Brooks and Lair 2005; Duniway et al. 2010; Duniway and Herrick 2011; Keshkamat et al. 2012). Additionally, different road ownership or use might call for differing management actions. For example, to support land management decisions, it might be important to separately analyze impacts due to roads maintained by the county, roads installed for energy development, and recreational off-road vehicle trails. Of course, the levels of stratification achievable will depend on the resources available for plot evaluations—there needs to be at least one, and preferably three or more, plots in each stratum.

The general goal of this paper is to develop, describe, and test an approach for using IIRH to systematically evaluate road impacts across large, diverse areas. Specific objectives of the test application are to evaluate (1) the usefulness of the various strata used in sample design, (2) the repeatability of IIRH evaluations conducted independently by multiple observers in road-disturbed plots, and (3) the relative impact of roads at the landscape scale in a semiarid landscape. Finally, based on results from the test application, we discuss application considerations for the developed approach and provide recommendations for further improvement.

METHODS

Study Area

Our study area for developing and testing an approach for assessing potential impacts of road development and use on rangeland health was a semiarid landscape in southern New Mexico (centered on lat 32°29′8.6″N, long 105°52′6.0″W; Fig. 1). The study area includes three BLM grazing allotments in areas jointly managed by Ft. Bliss Army Base and the BLM with a total study area of 25 662 ha. Two of the allotments are adjacent to one another and located in MLRA 42.4 (elevation 1 432–1 917 m), and the third is located approximately 20 km to the west, slightly lower in elevation (1 221–1 294 m), and in MLRA 42.2. The study area encompasses a wide variety of geomorphic surfaces and associated soils including limestone hills, alluvial fans, valley bottoms, alluvial planes, and eolian sands. Plant community composition in the study area varies with soils, elevation, and landscape position but the historic plant communities (as described in the Ecological Site Descriptions; Table S1 (available at http://dx.doi.org/10.2111/REM-D-11-00130.s1) in the majority of the study area are warm season grasslands or mixed communities co-dominated by warm season grasses, shrubs, and half-shrubs. Representative dominant species include mesquite (*Prosopus glandulosa* Torr.) and black grama (*Bouteloua eriopoda* Torr.) on sandy sites, creosote (*Larrea tridentata* DC.) and black grama on gravelly sites, and tarbush (*Flourensia cernua* DC.) and tobosa (*Pleuraphis mutica* Buckley) on loamy sites (Table S1). The 1971–2000 average annual precipitation for the study area is 328 mm (range 273–482 mm) with approximately 50% falling during the summer months (June through September; PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, accessed 8 April 2011).

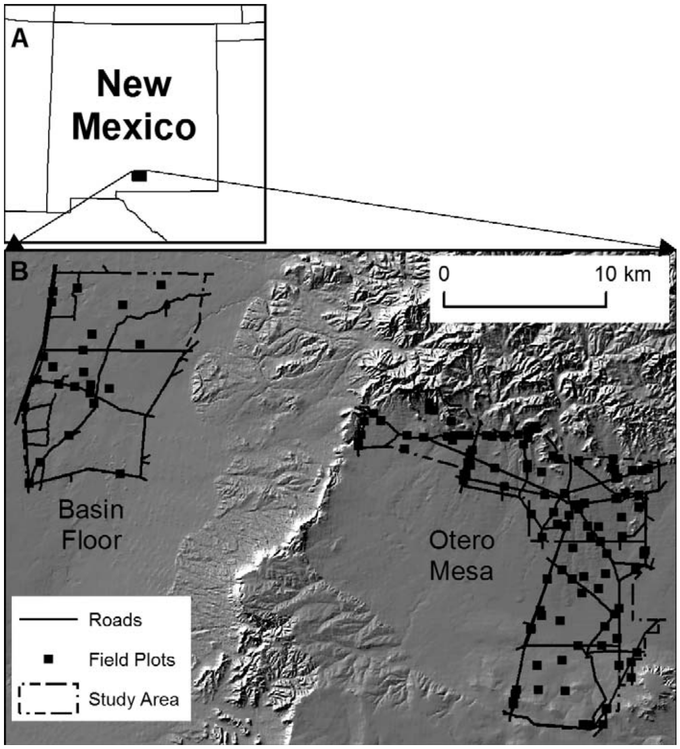

Figure 1. **A**, Study area location. **B**, distribution of plots.

Stratification

To evaluate road impacts across the heterogeneous study area, we developed a stratified random sampling approach to plot selection to ensure that study plots represent the broad range of ecological sites present and included areas both near and far from roads. To achieve this, we first stratified using five groups of ecological sites and three types of road (Table 2 and Table S1). More ecological sites were mapped in the study area than could be used as strata (at least 10), so similar ecological sites were grouped together to create five ecological site groups based on similar potential composition and production (ES groups; Table S1). The existing soil survey (Sprankle 2003) was used to create a map predicting the spatial distribution of these ES groups based on the ecological sites correlated with the dominant map unit component. To generate a study area layer of all current roads for stratification, data were compiled from

Table 2. Hectares of each road and ecological site group strata used in selection of field plots.

	Ecological site group[2]					
Road[1]	Gravelly	Lithic	Loamy	Draw	Sandy	Total
Major	102	23	152	33	42	351
Minor	152	44	469	25	242	932
Nonroad	3 867	2 223	9 862	768	7 658	24 379
Total	4 122	2 290	10 482	826	7 942	25 662

[1] Based on a ~23 m buffer from road edge.

[2] As mapped by the NRCS Soil Survey.

Ft. Bliss and Otero County current road layers as well as by digitization of roads not previously mapped using 1 m aerial photos from 2005 (Digital Ortho Quads [DOQs]). The road strata included all areas within ~23 m of roads. This was done by buffering road centerlines of wide (~4 m) county roads by 27 m and narrower (~2 m) roads by 25 m. This buffering distance was chosen to capture an area wider than the area directly impacted by road installation (~2–6 m) but narrow enough such that plots (see Field Data Collection) would always include some road. Roads were classified as either "Major" or "Minor" based on road layer classifications and interpretation of the DOQs. Major roads included roads maintained by Otero County (some of which had graveled surfaces) and roads that had improvements that were clearly visible on the imagery, such as ditches and drains. All other roads, including minimally bladed and unbladed roads, often referred to as "two-tracks" or "jeep tracks," were classified as Minor.

To further increase spatial balance in our samples, we applied a spatially balanced random sampling algorithm based on generalized random-dimensional space (GRTS) to each road type by ES group strata (Stevens and Olsen 2004; S-Draw GRTS sampler, version 1.0; West, Inc.; Cheyenne, WY). The input population for the GRTS procedure was a regular grid of 50 m spaced points that covered our study area. More samples than needed were drawn from each road by ES group strata to allow for further stratification by image interpretation.

To maximize detection of problem areas along roads, we further stratified our random sample of road points based on apparent impact. No GIS layer of an ecological process indicator (e.g., percent bare ground) existed, so a sampling approach was used (e.g., Karl et al. in press). The GRTS sampling procedure includes a randomized order of selection. Following this order, road plots in each road type strata were visually stratified as either "high" or "low" impact by overlaying 50 × 50 m plot outlines onto 0.6-m resolution QuickBird imagery in GIS using ArcMap version 9.3 (ESRI; Redlands, CA). Impacts were determined by visually comparing patterns of vegetation, bare ground, and erosional features in the road plots to areas in the same soil map unit and with similar topography, but far from roads, trails, and associated disturbance. Plots were classified as high impact if one or both of two criteria were met: visually estimated deviation in vegetation cover or bare ground of greater than approximately 30% from surrounding area, or any observable increased density of erosional features. Based on previous field-based studies (Godinez-Alvarez et al. 2009), we recognize that these visual estimates are likely to be highly variable and thus less likely to improve sampling efficiency. They were applied in this case to provide a very rough, rapid estimate and test their utility as a sampling strata. Plots that were not high impact were classified as low impact. This procedure was repeated until four plots were selected for each impact class in each road type by ES group strata (80 road plots).

To test if the ecological condition of areas near roads was different than areas far from roads, an additional six plots were selected in the non-road areas (center of plots > ~23 m from a road edge) of each ES group using the GRTS procedure for a total of 30 nonroad plots.

Field Data Collection

Stratification with soil maps was used to increase the likelihood that the field plots would capture the ecological sites of interest. The soil map units on which the stratification were made, however, are not homogenous and (like most soil map units worldwide) include several different soils. Therefore, at each plot the ecological site was identified using either small soil pits or auger holes.

Field work was conducted from September through November 2008. An interdisciplinary three person team (representing the soil science, range science, and botany disciplines) each of whom had extensive experience with IIRH, including at least two 1-wk formal IIRH trainings, conducted independent evaluations following Pellant et al. (2005). In this study, an ecological site-specific "reference matrix," which describes the conditions expected for each indicator at each level of departure, was used to maximize precision (Pellant et al. 2005). Independent observer evaluations of IIRH indicators and attributes were then followed by a consensus evaluation.

In plots that contained a road, the roadway was not always included in the evaluation. The roadway of Major roads was excluded from evaluations but the roadway of Minor roads was included (Fig. 2). This decision was based on the very different management and relative permanence of these two classes of roads. Major roads (as defined in this study) are likely to be maintained and used for perpetuity. For these types of roads, where restoration was not likely and assessing the status of ecological processes in the roadway was not informative for management, we concluded that conducting IIRH evaluations in the roadway was not necessary. Minor roads, however, were not consistently maintained, appear to receive only sporadic use, and are often candidates for closure during revision of travel management plans (e.g., Graves et al. 2006; BLM 2008). Therefore roadways of Minor roads were included in IIRH evaluations.

Quantitative estimates of bare ground, litter cover, and soil aggregate stability, which are necessary for IIRH, were calculated from data collected along three 25-m transects at each plot (following Herrick et al. 2005). Transects were placed in a hub-and-spoke pattern originating 5 m from the center of the plot and spaced at 120° intervals. To avoid a systematic error in road plots (several roads are oriented with the cardinal directions), the orientation of the transect pattern was randomized for each plot. Transects were allowed to cross the roads and samples collected from the roadway noted. Bare ground and litter cover were estimated using line point intercept (LPI) sampling with a point spacing of 50 cm. Soil aggregate stability samples were collected from each plot and analyzed using a field kit (Herrick et al. 2001). Six surface and subsurface samples were collected along each transect (total of 18 surface and subsurface samples at each plot). Sample locations were classified as either protected by perennial vegetation (> 50% foliar cover) or not protected by perennial vegetation (< 50% foliar cover). For all methods, samples collected in the roadway were not considered when conducting IIRH evaluations of Major road plots. Results were used to inform the IIRH evaluations but are not reported here.

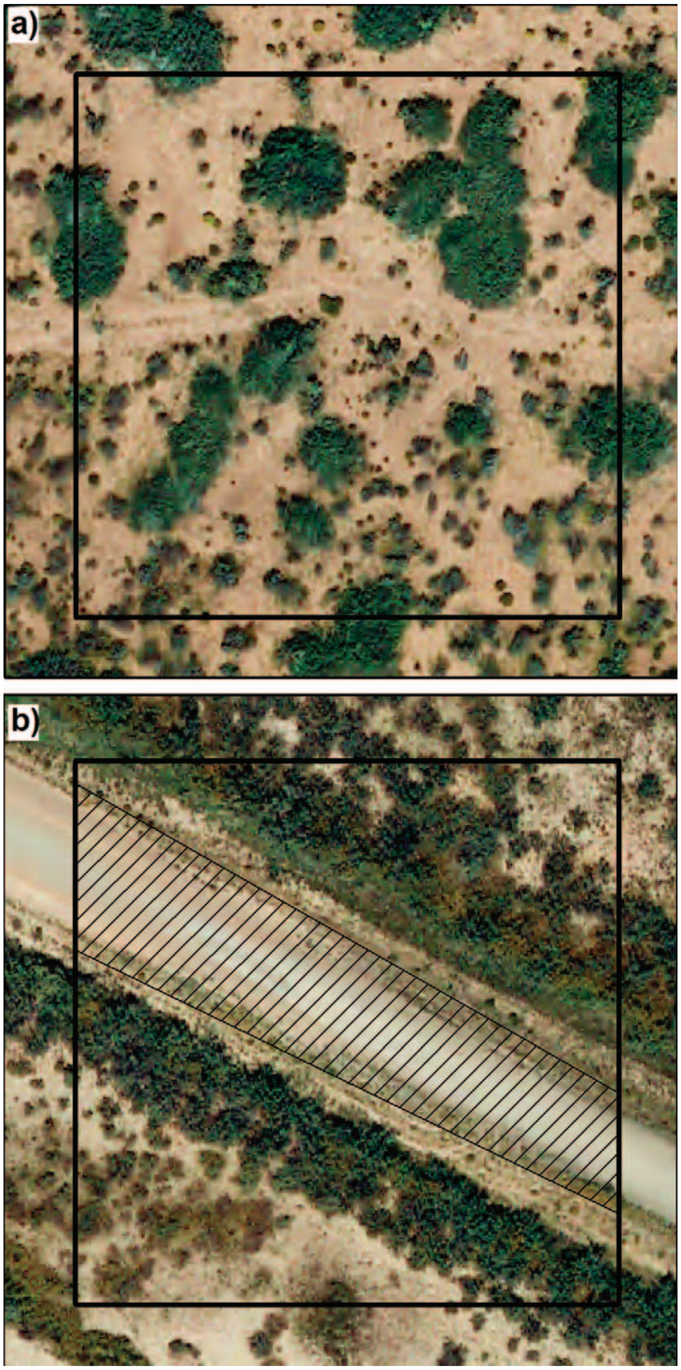

Figure 2. Example of 50 by 50 m plots on differing road types: **A**, single Interpreting Indicators of Rangeland Health (IIRH) evaluation that includes the road is completed for entire plot and **B,** an evaluation for all nonroad areas is completed (cross-hatched area ignored). In **B**, a separate evaluation can be completed for the road area. How the road is treated in IIRH evaluations should be determined based on road classification, usage, or other management considerations and be included with route inventory information.

Statistical Analysis

We conducted three sets of statistical analyses to meet each of our three objectives. Unless specified otherwise, groups of plots were contrasted using χ^2 test statistics testing the null-hypothesis that the distribution of IIRH departure ratings in the two groups of plots were not different (PROC FREQ; SAS version 9.2, SAS Institute Inc., Cary, NC).

To evaluate the usefulness of the strata used in our sample design, we conducted three sets of analyses. First, to test whether our method for detecting road impacts with imagery was consistently related to field data, we tested whether the mean IIRH attribute and indicator departure distributions differed between high- and low-impact road plots (Friedman's test blocking on road type and ES group). Second, to test if stratification by road type was useful, we tested whether the mean IIRH attribute and indicator departure distributions differed between Major and Minor road types (Friedman's test blocking on apparent impact and ES group). The Friedman's test, however, has low power to detect association when the pattern for some strata is in the opposite direction of the patterns in other strata. The pattern of attribute departure of Major and Minor road plots was not consistent across strata. Therefore, we also used the stratum-adjusted Pearson χ^2 statistic (Cochran-Mantel-Haenszel General Association Statistic) to test if there was a relationship between departure ratings and road type for at least one stratum. We also generated area estimates of each attribute-level departure class for each road type using the probability of selection and strata areas (using only the first four plots that were randomly selected in each road type as above). The roadway was approximately 16% of the Major road strata area ($\sim$55 ha). IIRH evaluations were not done in this area. To account for this in estimating the hectares in each departure class, IIRH attributes were assumed to be in extreme-to-total departure in the roadway of Major roads. This assumption was validated by observations at each of the Major road plots. Third, to assess how ecosystem processes varied among ES groups, we tested whether the mean IIRH attribute and indicator departure distributions differed among ES groups (Friedman's test blocking on road type [Major, Minor, and nonroad]). Finally, to evaluate if road impacts differed among mapped ES groups, and by extension if stratification by ES group was useful, we compared the IIRH attribute departure distribution of road and nonroad plots within ES groups using Mantel-Haenszel χ^2 exact test.

To evaluate the repeatability of IIRH evaluations in road-disturbed plots we conducted statistical analyses testing for observer bias and agreement. To test for bias, we investigated whether there was any systematic pattern in attribute ratings among the three observers by comparing the relative rankings of the independent IIRH assessment departure ratings across plots. The frequency of each observer's relative ranking across all road and nonroad plots for each attribute was compared using Friedman's test blocking on plot. To test level of agreement, we compared the range in attribute ratings among the three observers in road and nonroad plots (0=all three observers agreed; 1=at least one observer was one attribute rating different than another observer; 2=at least one observer was two attribute ratings different than another observer). The frequency of attribute departure rating ranges (0, 1, and 2) was then calculated for road and nonroad plots for each IIRH attribute. Whether the road was included or not in the evaluation might affect agreement; therefore this test was done separately for the two road types. Although IIRH ratings (either at the indicator or attribute level) are not necessarily

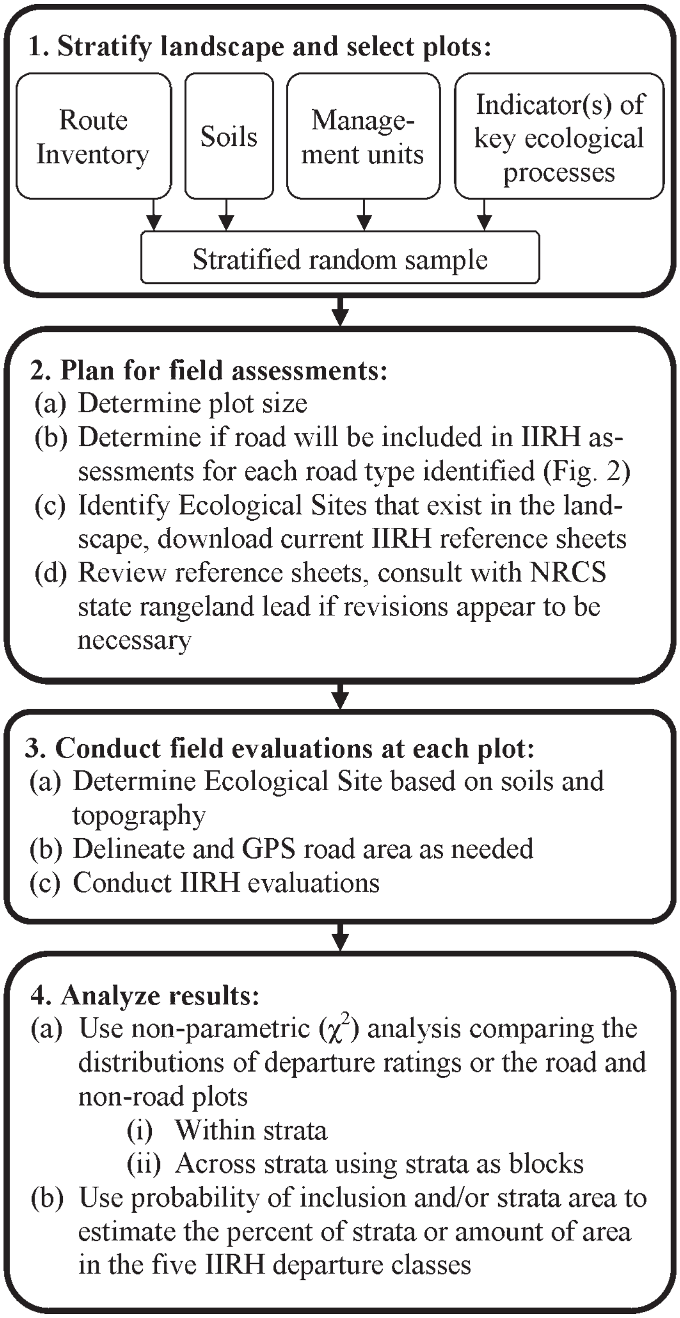

Figure 3. Flow chart of new approach for detecting road impacts with Interpreting Indicators of Rangeland Health (IIRH).

evenly spaced in a conceptual ecological process space (i.e., the distance between none-to-slight and slight-to-moderate is not necessarily the same as the distance between moderate-to-extreme and extreme-to-total), this approach does allow us to compare levels of agreement among observers without treating ratings as a continuous variable.

To evaluate the impact of roads at the landscape scale, we conducted two analyses. First, we compared the distributions of IIRH attribute departure classes in road and nonroad areas using a Friedman's test blocking on ES group. Because the road plots included two strata of differing representative areas (Major and Minor roads), we used the relative area of those strata as a weighting factor. Second, to evaluate which IIRH indicators were systematically different between road and nonroad plots across the landscape we conducted the same analyses as above but on the distribution of IIRH indicator departure classes. Because we did not have the weighting factors for our high- and low-impact strata necessary for landscape scale analyses, we did not use that level of stratification in these tests and simply used the first four plots that were randomly selected in each ES group by road type strata ($n=40$ road plots).

RESULTS

Analysis of Stratification Approach

A flow chart of the developed approach for detecting road impacts using a stratified random sampling design is depicted in Figure 3. In our test application, we did not have the resources available to support the additional field sampling required to examine effects of management unit (allotment) and maintain sufficient replication in each stratum to achieve our research objectives. Therefore we did not include allotment in our stratification.

Image Interpretation of Apparent Impact. Examination of IIRH attribute departure rating distributions for the two apparent impact strata indicates that differences in ecosystem processes detected through image interpretation of moderate resolution (0.6 m pixel) did not systematically correspond to field assessments at the attribute level ($P > 0.05$; Fig. 4A). The distribution of departure classes of Soil and Site Stability was slightly farther from potential in high- than low-impact plots (more than 50% plots Moderate or worse for high-impact). At the indicator level, there were significant differences in the distribution of four indicators ($P < 0.05$; Table 1). Three indicators are associated with Hydrologic Function and Soil and Site Stability (rills, gullies, and soil surface resistance to erosion) and one only Soil and Site Stability (amount of litter movement).

Road Type. The distribution of IIRH attribute departure ratings was similar for Major and Minor road types (Fig. 4B). On average, the distribution of attribute ratings was not different (Friedman's test for road type mean scores differ $P > 0.05$). However, for at least one ES group-apparent impact stratum combination, there was some relationship between road type and Soil and Site Stability attribute ratings (General Association Statistic $P < 0.05$). Evaluation of the area in each attribute departure class (Fig. 4C) indicates there are many more hectares in moderate or greater departure from reference in the Minor than Major road types. Of particular concern is the large amount of road area with degraded hydrologic function. There were four indicators with significantly different departure distributions between Major and Minor road types ($P < 0.05$; Table 1), three of which had more plots with ratings farther from reference in the Minor than Major road types (bare ground, soil surface structure, and soil compaction). Only one indicator, number of gullies and erosion associated with gullies, had greater departure from reference in the Major than Minor road types.

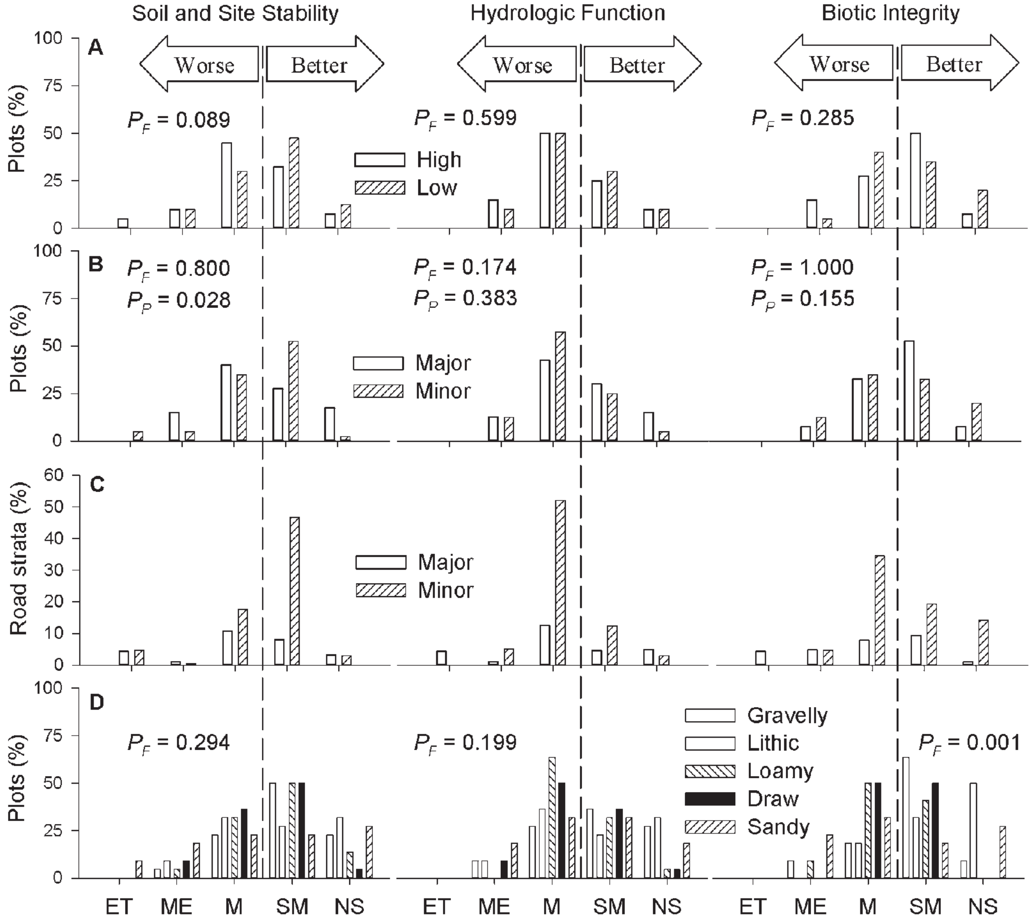

Figure 4. Interpreting Indicators of Rangeland Health (IIRH) attribute ratings for plots on or adjacent to roads for each of the three IIRH attributes for the **A**, two apparent impact strata (High and Low), and **B**, two road types (Major are maintained dirt or gravel roads with road excluded from assessment; Minor are non- or infrequently maintained roads with road included in assessment). **C**, Percent of the road strata (areas within ~23 m of road edge; 1 284 ha in total) in each IIRH departure class for the two road types investigated (roadway of Major roads assumed to be ET). **D**, IIRH attribute ratings for all plots in each of the five Ecological Site groups. P_F values are from Friedman's tests testing the null hypothesis that mean departure distributions do not differ. P_P values are from a stratum-adjusted Pearson χ^2 statistic testing the null hypothesis that there is no relationship between departure distributions and road type for any level of blocking factors. Blocking factors in **A** and **B** were five levels of ES Group and **A,** two levels of road type as blocks, or **B**, two levels of impact as blocks with $n=4$ plots per block. Blocking factors in **D** were three levels of road type [Major ($n=8$ plots per block), Minor ($n=8$ plots per block), and nonroad ($n=6$ plots per block)]. "Better" and "Worse" arrows and vertical dashed line between M and SM are provided to help interpret which groups are predominantly closer to reference condition (NS, none-to-slight; or SM, slight-to-moderate) vs. farther from reference condition (M, moderate; ME, moderate-to-extreme; or ET, extreme-to-totals).

Ecological Site. There were significant differences in mean attribute ratings among ES groups for Biotic Integrity but not Soil and Site Stability or Hydrologic Function (Fig. 4D). At the indicator level, there were several significant differences in the distribution of departure ratings among ES groups (Table 1). Nine of the 17 indicators significantly differed in mean departure rating, six of which are associated with Biotic Integrity. Comparisons of departure class distribution of the road and nonroad areas within the mapped ES groups suggest that roads negatively impact rangeland health primarily within a relative few mapped soil types (Fig. 5). Soil and Site Stability and Hydrologic function departure distributions differed significantly ($P < 0.05$) between road and nonroad plots in the areas mapped as Gravelly and Lithic ES groups. In the Loamy ES Group, significant differences were detected only in Soil and Site Stability. No differences were detected in the Draw or Sandy groups.

Repeatability of IIRH Assessments

Observers were within one rating of each other in all three attributes for $>93\%$ of all plots and there was no detectable difference in observer agreement among the three road type classes (Major, Minor, and nonroad plots) (Fig. 6). The analysis evaluating observer bias, testing whether one observer consistently rated plots with greater or less departure than the other two observers, indicates there was potentially some bias in the Soil and Site stability attribute ratings for Major roads among the three observers (Table 3). Inspection of the distribution of observer rankings suggests that this significant P value was due to one observer who was never the most negative (furthest from

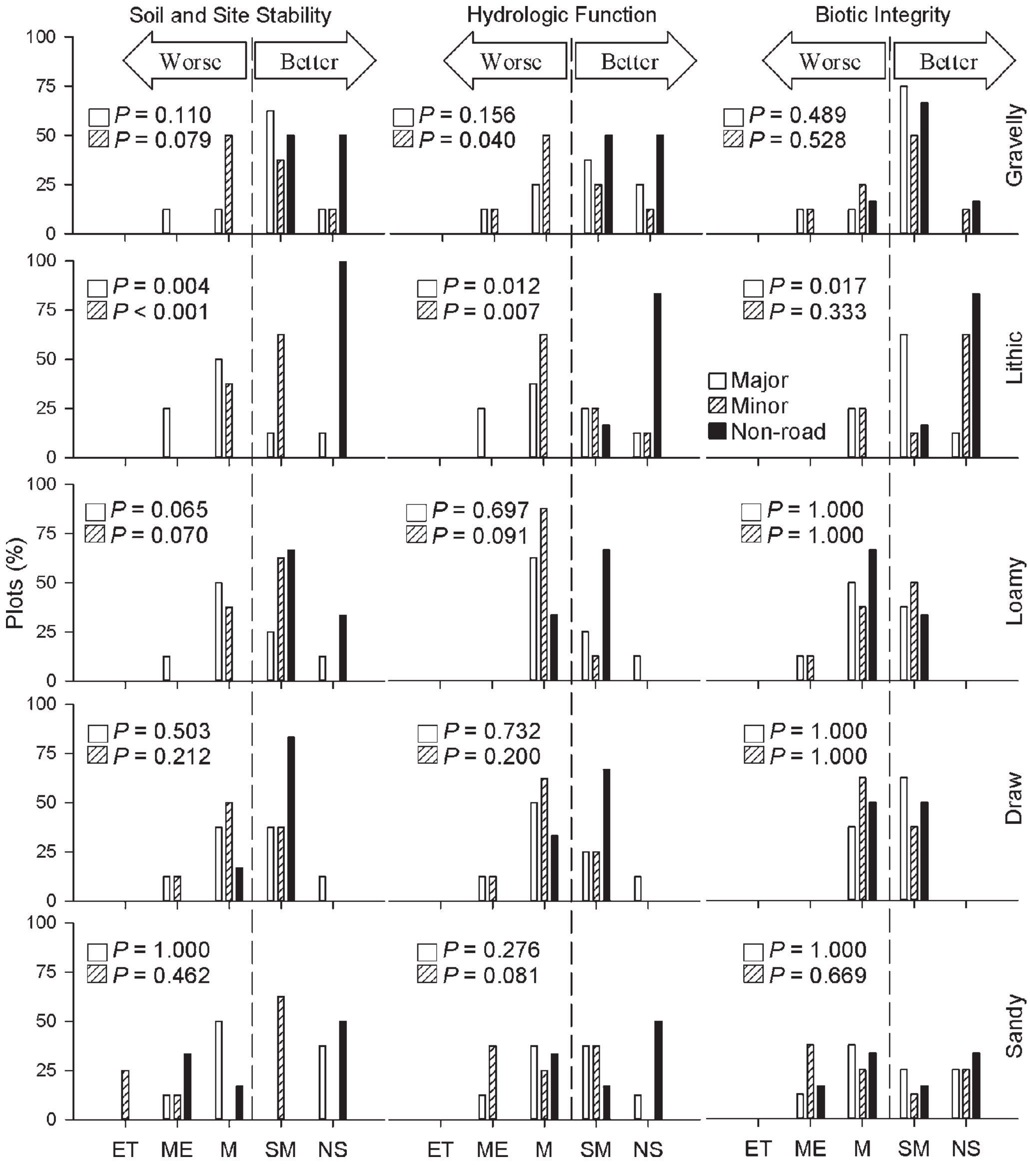

Figure 5. Interpreting Indicators of Rangeland Health (IIRH) attribute ratings for plots on or adjacent to roads and nonroad plots for each Ecological Site group (Gravelly, Lithic, Loamy, Draw, and Sandy; Table S1) and for each of the three IIRH attributes. Road plots are broken down into two types: Major (maintained dirt or gravel roads, road excluded from assessment) and Minor (non- or infrequently maintained roads, road included in assessment). *P* values are from Mantel-Haenszel χ^2 exact tests ($n=8$ road and 6 nonroad plots in each) comparing the distribution of the Major vs. nonroad (□) and Minor vs. nonroad (▨) class attribute departure ratings. See Figure 4 for additional information.

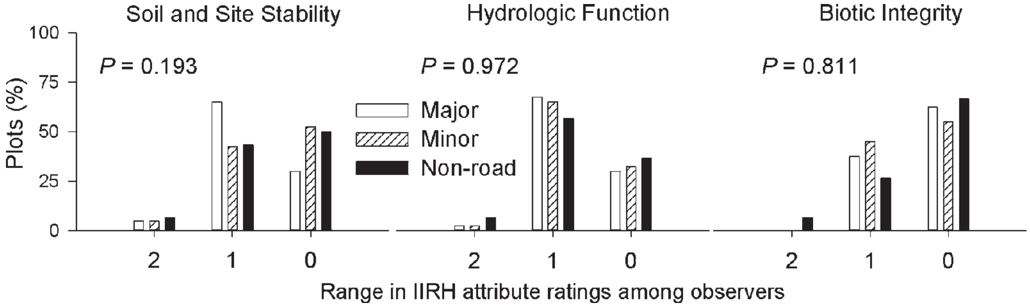

Figure 6. Range in Interpreting Indicators of Rangeland Health (IIRH) attribute ratings among the three observers (0=all observers had same departure rating, 2=observers differed by two departure classes) within plots and frequency of occurrence in each road type (nonroad, Major road, and Minor road) and for each of the three IIRH attributes. *P* values are from Mantel-Haenszel χ^2 exact tests ($n=40$ Major, $n=40$ Minor, and $n=30$ nonroad).

Table 3. Results of χ^2 statistical tests of bias among the three IIRH observers in plot attribute ratings for the three classes of roads evaluated (Major roads, Minor roads, and nonroad plots). Attribute cell values are *P* value results from Friedman's test blocking on plot.

		Attribute[1]		
Strata	*N*	SSS	HF	BI
Major	120	0.016	0.107	0.247
Minor	120	0.368	0.289	0.249
Nonroad	90	0.076	0.260	0.424

[1] SSS, Soil and Site Stability; HF, Hydrologic Function; BI, Biotic Integrity.

reference) of the three observers for the Soil and Site Stability attribute on Major roads (40 of 110 total plots evaluated).

Road Impacts on the Landscape

Landscape-scale analysis of rangeland health along road corridors in a semiarid rangeland in southern New Mexico (Fig. 1) indicates that, on an area basis, the IIRH attribute with the greatest departure from reference is Hydrologic Function with ~73% of the road area in Moderate departure or worse (Fig. 7). For Soil and Site Stability, only ~33% of the road corridor is in Moderate departure or worse. The distribution of departure classes for Soil and Site Stability and Hydrologic Function were significantly different in road and nonroad areas ($P < 0.05$). No significant differences were detected in Biotic Integrity. Analyses at the indicator level (Table 1) suggest that these attribute differences were driven by six indicators (rills, water flow patterns, bare ground, litter movement, soil surface structure, and soil compaction), all of which had greater departure from reference on average in road than non-road plots. Annual production was also farther from reference in road plots; however, these differences were insufficient to result in a change in Biotic Integrity, the one attribute with which it is associated (Table 1).

DISCUSSION

The test application on a semiarid landscape in southern New Mexico (Fig. 1) clearly demonstrates that the approach developed (Fig. 3) is sensitive to road impacts across a broad range of ecological sites (Fig. 7) but that not all the levels of stratification used were useful (Fig. 4). Analysis of the repeatability of IIRH applied to road plots indicates that the method is repeatable but consensus evaluations based multiple observers (as was done in this study) should be used to minimize risk of bias. Additionally, this approach is likely cost effective with each IIRH evaluation taking on average ~1 hr for a team of three to complete.

Which Strata to Use?

The lack of systematic differences in any attribute between road plots in the two levels of apparent impact stratification (Fig. 4A) suggests that this additional level of stratification did not account for substantial landscape variability in ecosystem processes, even though remote sensing of plant cover (e.g., Booth and Tueller 2003; Karl 2010) and road impacts (e.g., Okayasu et al. 2007; Wei et al. 2008) has been successfully used in other studies. The presence of some significant differences at the indicator level (Table 1) suggests that there were some differences in processes among high- and low-impact strata but they were not sufficiently consistent and/or strong to result in a systematic difference at the attribute level (Fig. 4A). There are several potential methodological reasons why our approach to detecting road impacts from imagery was not consistently related to field data, including insufficient resolution of imagery and/or precision of the method.

However, another likely contributing factor is the necessarily low precision of the soil survey information. It is possible that the increases in bare ground or increased frequency of erosion features we observed on the imagery in some "high"-impact plots were not due to road effects but within-soil map unit variability in ecological potential associated with multiple soils included in the same map unit. For example, in a map unit that was predominately a highly productive ecological site (e.g., Loamy) an isolated inclusion of a lower productive site (e.g., Gravelly) along a roadway would appear to have higher bare ground and thus be classified as "high" impact even though the difference in cover was not due to road effects.

A major problem with the impact strata used here is that we did not have a continuous GIS layer to use for stratification but instead relied on a sampling approach to stratify by impact. The number of plots classified into high- and low-impact classes during stratification (generally less than 20 in each road type by ES group strata) is not likely sufficient for estimating the proportion of the landscape in high- and low-impact strata. Therefore, use of this level of stratification when calculating area estimates (e.g., Figs. 4C and 7) would have required additional sampling of the landscape with image interpretation to determine the approximate strata weights. The results

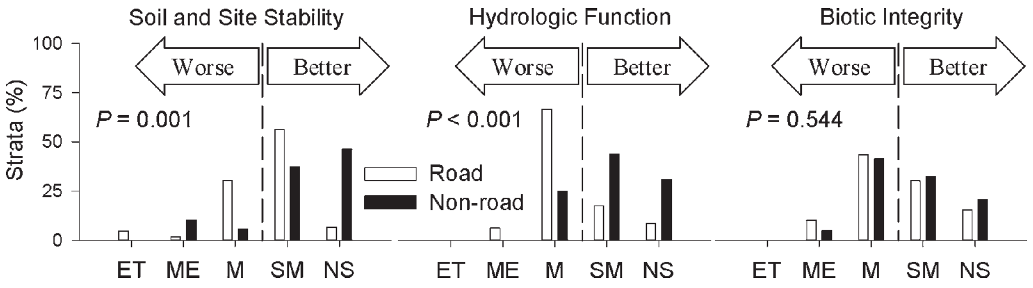

Figure 7. Proportion of road and non-road area in each IIRH departure class for each of the three IIRH attributes. *P* values are from Friedman's tests testing the null hypothesis that mean departure distributions do not differ ($n=8$ road and $n=6$ nonroad plots per block with five levels of ES Group as blocks). See Figure 4 for additional information.

presented here do not indicate that stratifying by apparent impact with image interpretation is a useful or an efficient use of resources.

Stratification by road type does appear to account for some important variability in ecosystem resilience to road impacts across the landscape in at least one attribute of rangeland health (Soil and Site Stability; Fig. 4B) suggesting it is a useful type of stratification to include. The opposite trends in departure ratings among some indicators is likely due to a combination of differing processes and differences in application of IIRH between the two road types. The greater departure from reference in gullies for Major than Minor roads is likely due to more frequent, larger modifications of surface hydrology in Major roads resulting from construction of ditches and drains. By design, these engineered drainage features capture, concentrate, and release overland flow to down slope locations. Such concentrated flow will have greater erosive force—sometimes enough force to initiate the formation of gullies.

The greater departure from reference in bare ground, soil surface structure, and soil compaction in Minor than Major road plots was likely due to the inclusion of roads in Minor plot IIRH evaluations and exclusion of the road in Major plot IIRH evaluations. In nearly all of the Minor roads, road development and/or vehicle traffic caused a large reduction in vegetation and litter cover and compaction of soils in the roadway. The departure descriptions for all three of those indicators are very sensitive to changes that occur even in discrete areas of the plot. Thus, even if nonroad parts of the plot were at or near reference, the indicator would still be consistently rated with some departure just based on the high amounts of bare ground, loss of soil structure, and increased compaction in the roadway.

Stratification by road type is also useful because results for the different strata contain information potentially important for management. For example, there are more than double the hectares in the Minor than Major road corridor (Table 2; Fig. 4C). However, the distributions of attribute departures are not significantly different on average between the two road types (Freidman's results; Fig. 4B). Based on the results of this study, a future travel management plan could support concentration of traffic along fewer well-designed Major roads and closure of some Minor roads. To minimize risk of gully development along Major roads, extra care should be taken in ditch and drain design to reduce erosive force of the concentrated overland flow.

Stratification by ecological site (ES group) also appears to account for important differences in responses across the landscape. In contrast to all other analyses, the only attribute that was significantly different among ES groups was Biotic Integrity (Fig. 4D). Because the IIRH method already accounts for ecological potential, this difference in the biotic component is likely due to differences among mapped ES groups in the intensity of other disturbance activities (e.g., grazing), resilience to those activities, or resilience to other stressors such as climate fluctuations.

The results of road impact analyses within ES groups (Fig. 5) accompanied by area soil maps can be applied to transportation planning efforts. The results from this study suggest that some of the greatest changes to ecosystem function are due to the presence and/or use of roads in the Gravelly and Lithic map units. However, such results should be interpreted with caution since the distribution of actual ecological sites (as identified it the field) can be quite different from that expected based on the soil map (Table 4). For example, in the Lithic group half of the Major road plots were actually Loamy, which likely contributed to the significant attribute differences between Major road and nonroad plots, particularly in Biotic Integrity (Fig. 5). Mapping inaccuracies were especially acute for the Draw and Gravelly ES groups in which very few of the plots were identified in the field as belonging to the ES group expected based on the soil map. Therefore, while results of analyses based on mapped soil types are appropriate for planning purposes, insights into mechanisms and soil processes that govern resilience to roads are likely limited. New soil mapping technologies (e.g., Boettinger et al. 2010) may help to improve predictions of the spatial distribution of ecological sites across the landscape and thereby simultaneously improve stratification efforts and our ability to precisely manage large landscapes based on ecological potential.

Another data source that could be useful for stratification, though not considered here, is some measure of road-landscape hydrologic interactions (e.g., Duniway and Herrick 2011). Some of the most significant impacts of road development and use are to rangeland hydrologic function (Fig. 7; Duniway et al. 2010). A GIS analysis that accounts for road alignment and configuration relative to the direction and potential amount of overland flow (based on digital evaluation model-derived hydrologic metrics) could control for a large amount of among plot variability in IIRH attribute departure ratings.

Maximizing Observer Repeatability

The very small range in attribute ratings among observers at the vast majority of road plots ($\geq 95\%$ plots ≤ 1 departure class; Fig. 6) suggests application of the IIRH method in road-affected areas is repeatable. These results are consistent with past research (Duniway et al. 2010) and with the level of precision the method was intended to produce (M. Pellant personal communication, May 2011). However, the slight observer differences detected in Major road plots in this study (Table 4) and past work (Wyoming study area in Duniway et al. 2010) suggest extra care is needed when evaluating the Soil and Site Stability attribute in highly disturbed plots. These results also support the recommendation by Pellant et al. (2005) that IIRH evaluations be completed by an interdisciplinary team where possible.

Road Impacts on the Landscape

The demonstrated sensitivity of IIRH to road effects (Fig. 7) is consistent with past work applying IIRH to roads at the plot level. Duniway et al. (2010) found that the departure distribution of Soil and Site Stability and Hydrologic Function were different between road and nonroad plots across three ecosystems (one ecological site in each of Wyoming, Utah, and New Mexico). The lack of differences in Biotic Integrity detected in this study is likely due to the scale of measurements (50 by 50 m plot). Duniway et al. (2010) found significant differences in Biotic Integrity between areas within 5 m of the roadway and nonroad areas (Utah and Wyoming) but no differences at distances >5 m away. This relatively fine scale variability is visible in Figure 3. Surprisingly, the indicators most sensitive to road impacts (those with significant differ-

Table 4. Distributions of actual Ecological Site groups (as identified in the field) within each Ecological Site group as mapped, broken down by Major road, Minor road, and nonroad plots.

Mapped ecological site group	Road	Field identified ecological site group				
		Gravelly	Lithic	Loamy	Draw	Sandy
		%				
Gravelly	Major[1]	50	0	25	0	25
	Minor[1]	0	0	25	0	75
	Nonroad[2]	0	0	67	0	33
Lithic	Major	13	25	50	0	13
	Minor	0	75	0	0	25
	Nonroad	0	67	17	0	17
Loamy	Major	13	0	88	0	0
	Minor	0	0	75	0	25
	Nonroad	0	0	83	0	17
Draw	Major	13	0	63	25	0
	Minor	25	0	50	13	13
	Nonroad	17	0	33	33	17
Sandy	Major	25	0	0	0	75
	Minor	0	13	13	0	75
	Nonroad	0	17	0	0	83

[1] $N=8$ plots for Major and Minor road types.
[2] $N=6$ nonroad plots.

ences between road and nonroad plots in Table 1) were more similar to those reported by Duniway et al. (2010) for a Loamy ecological site in Wyoming than the Gravelly ecological site investigated in southern New Mexico. This is likely due to the similarity in soils between the two landscapes investigated (mostly Loamy in this study; Table 4). The similarity in IIRH indicators that were impacted by road development in the Loamy soil in Wyoming and this study suggest that even though the climatic regimes are fairly different, the mechanism by which roads impact processes was likely similar. Additionally, there are three indicators that were consistently different between road and nonroad plots in the results presented here and in all three ecosystems investigated by Duniway et al. (2010): bare ground, soil surface structure, and soil compaction. These similar results suggest that future monitoring efforts to detect road impacts should include indicators that capture these key properties. Based on results presented here (Table 1) it is possible that a reduced number of IIRH indicators could be used for detecting road impacts. However, due to variability in road impacts based on soil type, landscape position, and climate (Duniway and Herrick 2011), the suite of key indicators required will likely vary among ecological sites (Duniway et al. 2010).

IMPLICATIONS

The results presented here have several important implications for application of the proposed approach (Fig. 3) for detecting road impacts. (1) Strata should be selected that are either management relevant, account for landscape variability, or, ideally, both. Results from the test application indicate that the ecological sites and road type strata meet these requirements but apparent impact stratification does not. (2) The decision to include or exclude the roadway from plot IIRH evaluations has implications for both the repeatability and results of those evaluations. (3) IIRH evaluations should be completed by a team where possible. (4) Interpretations of analyses based on mapped ecological sites should be interpreted cautiously due to the low precision of many rangeland soil maps.

In conclusion, the IIRH evaluation system, which is already widely applied to address landscape changes independent of cause, can be combined with a simple stratification system (road vs. nonroad) to successfully identify where increased degradation is associated with the presence or use of roads. The study, together with previously published studies (e.g., Miller 2008; Duniway et al. 2010; Herrick et al. 2010), demonstrates that IIRH can be successfully applied to landscapes with diverse impacts, including livestock grazing, recreation, and energy (including oil, gas, and alternative) development, and provide information needed to support adaptive management decision processes.

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