Effective Comparisons Among Land User Impacts

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"Data without generalization is just gossip." (Pirsig 1991)

Background

When the following concepts were first developed fifteen years ago, no consistent, quantitative method existed to allocate public or private land use among competing resource users. Since then, ecological impact and user conflict situations have only gotten worse, given a fixed land base and rising population, exacerbated by faster rising numbers and capabilities among motorized assistance for humans. If another treatment with the potential of resolving the related issues has appeared in the interim, it has been no more effective in reaching the public or government than my own preliminary presentation to the Ecological Society (Yorks 2000). Hence, it seems worthwhile to reexamine this integrative theoretical framework, so that a more effective national discourse might begin.

A primary American ideal is for equality of opportunity. Consequently, most users of public and private lands have been treated both legally and practically as nearly equivalent, not least when assessing fees for their passage. This has remained true even as human land uses are increasingly assisted by relatively much heavier and more powerful machines. Despite the clues for even casual observers that user classes (e.g., ATVs vs. hikers) have dramatic differences in their impacts to roads, plants, animals, and soils—within equivalent periods of use—there has been and remarkably little effort towards quantitatively evaluating their differential extent, and not surprisingly therefore, no scientific or managerial consensus about what they might be overall.

Meanwhile, it is thoroughly established that even small increases in the overall weight of an individual hiker and load carried will have significant consequences for trampled vegetation (Cole 1995a). For such plant and soil systems away from roads, relationships tied to weight tend to be more readily visible, and therefore assessable, than they are upon concrete. Even so, similar differential relative impacts have been shown for damage for highway surfaces (Pacchioli 1995). On solid pavement, it just takes bigger loads, and more repetitions of passage, for damage differences to become as obvious.

Despite the logical obviousness of relating weight, power, and distance travelled within a system to consequent damage, quantitative confirmations in detail of those relationships on and off roads has remained mainly in obscure literature. Their importance remains largely overlooked by other scientists, land managers, and the public. Absent, further, is a consistent framework for these results across user classes and contexts. That task has been hampered by idiosyncratic criteria and choice of variables among limited experiments that have been conducted. Further, legitimate general arguments tend to be submerged among controversial details tangential to the overall questions, and even these are inadequately resolved.

Arguments for similarity continue, for just one example, that snowmobiles and skiers affect wildlife equally, despite having such a conclusion apply only to studies with classic analytical errors in differentiating between per-contact responses and sums that do not include how many contacts that will be made per day when user travel distances are greatly different.

It would be considered laughable for public marinas not to charge for moorage in proportion to the size of boats, but that principle has failed to be applied on land, where differences in impacts are even greater than size alone might indicate. Similarly, it would be unimaginable for tollways to ignore distances. Nevertheless, entrants continue to pay little or no more in our national parks and forests to bring in a 10-ton motor home, although the latter can travel hundreds of miles in a day over a required massive supporting infrastructure, unlike hikers with a five mile capability and a 20-pound backpack. New fees proposed for public lands continue to fail to differentiate user classes among the size of vehicles—if any—that land users may bring, or for length and width of their contact paths. Accordingly, problems of increasing deterioration of public and private lands that result from heavier off- and on-road travel continue to increase nearly everywhere (Fig. 1).

To overcome that analytical impasse, the simplest part of physics accurately foretells the energy needed to get or change direction of such added mass in motion, to keep it going, or to stop it. A well-conditioned, 70 kg (150 lb) human will have a maximum output that approaches 250 watts (1/3 hp), but more typically applies 80 watts. However, that same human, now as a vehicle operator with a 150,000-watt (200 hp) fossil-fueled engine, gains an impact potential some 600 times greater when a truck is added to their land use activity. Even a 15,000-watt ATV (or motorcycle) out-powers an unassisted human by 160 times in typical use. Additionally, most vehicles' fuel-subsidized output can be sustained for a far longer period, expanded further by their potential for far higher speeds. Thus, they will be contacting a much greater area during typical day use. These potential energy output differences do not just disappear when applied to the environment (Fig. 2).

To address this problem more effectively, scientifically reliable measures must go on to resonate at the theoretical and policy determination levels. These must demonstrate more convincingly how increases in weight and power consistently: (1) disrupt more plants and other surface components, (2) penetrate more deeply into supporting soil, (3) extend the per user travel path, and (4) expand other impacts more widely, when compared to what a vehicle-free operator would do in a similar time period.

Better armed with a method for reliable relative impact calculations, land managers and landowners could allocate restrictions and fees fairly among competing users. More importantly for a democracy, affected groups should be more willing to accept limitations, since there would be a clear and objective basis for their application, with the concept of equal access brought back to a personal level. Given the earth's fixed land resource base, increasing human population, and accelerating reliance upon mechanized transportation, better relative ranking of impacts among competing land user groups seems vital. Targeted impact rankings for government and private ownership use would thereby address critical societal needs.

Methods

Among the greatest difficulties in approaching—either inductively or deductively—such a complex problem set for user interactions with the land arises with effectively separating the dominant forces from those of lesser general import. Concentrating upon nuances as they are encountered, rather than sticking to underlying characteristics, interminably lengthens discussions. These quickly tends to obscure the main points, no matter how locally valid or scientifically cogent their tangents may be those whose specialty they cross.

Effective approaches to big questions appreciate that calculated generalizations will not perfectly apply in all localized situations, but still can describe the most likely result across the greatest number of cases, with increasing accuracy as the equations are refined by discussion and testing. Their goal becomes not perfection, but to be notably better than the existing dearth of capability for comparative analyses.

To initial integrate impact application hypotheses, American and Russian textbooks on off-road vehicle design (e.g., Wong 1978 and Ageikin 1981) provided technical information pre-bundled into mathematical formats. Vehicles may have evolved somewhat since, but their underlying principles remain constant. However, their mathematical derivations and predictions continue with little connection for subsequent implications to environmental responses.

In response to that lack, a computer spreadsheet was used to organize the vegetation response literature database of Yorks et al. (1997), which allowed more quickly testing predictions from the engineering expectations. Potential land users from extant studies were divided into groups by their physical size, weight, and available power. A dynamic linear programming optimization approach, based on that described in mathematical detail by Miller et al. (1980), was pursued to hone in on optimal relationship, wherein combinations and coefficients were tested iteratively until a single, comprehensive, predictive equation emerged with the most consistent explanatory pattern, after rechecking against the complete database. Results from a consequent range of possible integrative equations were displayed in tabular format across the user groups.

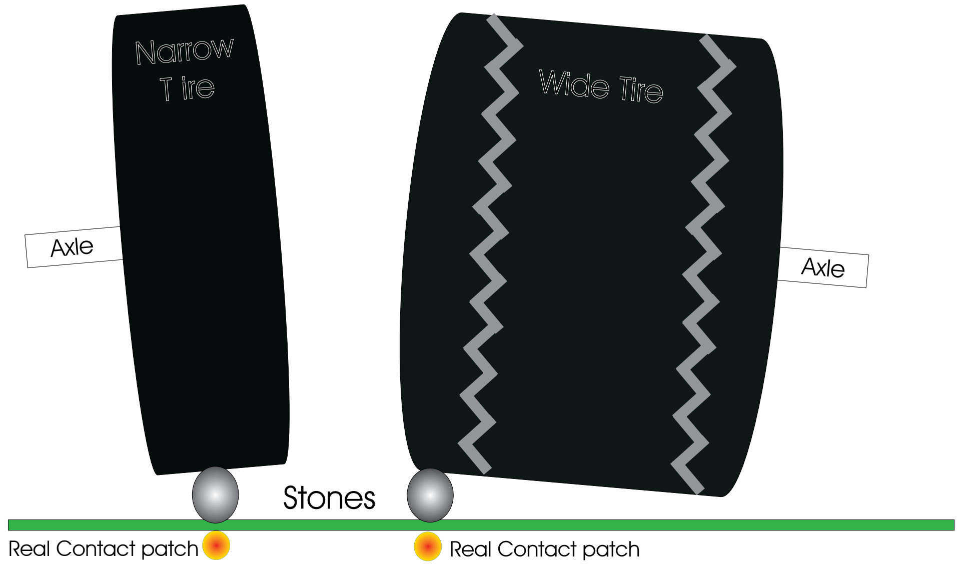
Results: The Dominating Components

(1) Weight

During passage of any object over any piece of ground, the net downward force (i.e., the portion of the overall pressure that is delivered directly to plants, soils, or road surfaces) is almost always primarily determined by the total weight involved. Acceleration, the changes in such pressure inputs (whether positive, negative, or from turning) can add to overall stress, of course, but it usually acts in a more horizontal direction. Weight is so obviously differential in impact potential, e.g., having a butterfly landing on one's foot versus an elephant or truck rolling over it, that further experimental proof should not be required. Yet, too often, those who have attempted to calculate effects have overlooked the related elementary truths. The first consideration that must be addressed when comparing user groups is that all passing weight must be supported in some way by either plants or soil.

Whenever downward forces reach threshold values, initially flexible absorption tends to change suddenly into collapse or other disruptive movement. For most plants, breakage begins with inputs far less than what most vehicles weigh. Many of these thresholds are crossed within a single exposure, while for others repetitions can be visualized as like a door suddenly giving way to a battering ram. Additional damage often then arises because broken or compacted plant surfaces are more open to microbial action (Rickard and Brown 1974) and frost (Watson et al. 1966), as well as from moisture loss. Illustrated by the development of potholes, washboarding, and rutting, roads are not immune from similar phenomena.

Exemplifying how obscuring detail can fade away is how wider tires tend to fail to reduce overall impacts of mass, contrary to expectations from one commonly believed parameter, static load. Objects in motion tend to distribute their weight very unevenly, placing their entire weight onto perhaps surprisingly small spaces. This is easily visualized in the hooves of a walking horse or bicycle tires, but also occurs when wide tires ride up on even small stones or plants as they pass over them, because functional tires are less instantaneously flexible than a plant or other objects needs them to be (Fig. 3).



Where such intensive action does not occur, wider tires merely extend the area impacted, since the weight still exceeds plant capabilities to absorb. Even the allied, thought-to-be distributive, presence of snow, contrary to beliefs of snowmobilers, does not protect plants and soils underneath from an absolute relationship between total weight passing and eventual damage. Supporting experimental observations have been made by Radforth 1972, Kerfoot 1972, Greller et al. 1974, and through personal observation, with Reaves and Cooper 1960 adding that weight-related effects go notably deeper into soils than are commonly tested.

Whenever downward forces reach a threshold value, an initially flexible absorption by roads, soils, or plants will change suddenly into collapse or other disruptive movement. For most plants, breakage begins with inputs less than common vehicle weights. Some thresholds will be crossed within a single exposure to trampling stress, while repetitive releases can be visualized as like a door suddenly giving way to a battering ram. Additional damage then arises because broken or compacted plant surfaces are more open to microbial action (Rickard and Brown 1974) and frost (Watson et al. 1966), as well as moisture loss.

Selectively focused downward forces (and their consequences) can be exacerbated by horizontal weight transfers during straight-line acceleration, cornering, or braking. That additional impacting force may be readily when vehicles squat toward the rear when moving off sharply, leaning to the outward side during turns, and diving toward the front in stopping, and are readily calculable with equations from basic physics. Each these effects is magnified for the vegetative or soil recipients of those forces, in proportion first to the weight and, secondarily, to the power involved.

(2) Power

To accelerate each increment of mass requires additional power, whether to change speed or direction, to move against gravity uphill, or to compensate for the effects of friction, including mechanical or from passage through air. As physical size increases, more power is also required to overcome the additional correlated resistances. The net is readily calculable from basic physics and engineering.

Most of the energy dispersed from power applied to any moving object passes directly to the soil and its coverings, including plants or pavement. Whatever is contacted in the process must in some way absorb that energy. Eventually, though only tangential to immediate land use comparisons, even the fractions of energy that are indirectly released as internal friction or other inefficiencies, such as engine idling, also come back to affect soils and vegetation through increased air pollution and global climate change. No power releases simply disappear.

Behavioral differences also apply, for example, as more powerful ATVs or snowmobiles, or even the mechanical advantage provided by mountain bikes, make users more capable of overcoming landscape resistance, which allows penetration into more sensitive areas. For relative impact calculations, however, the effective principle remains that if there is power available to apply, it will be used, with a likelihood not likely to differ greatly across land user classes.

(3) Wideness

Overall width first defines the area over which impacting power and weight will be spread. While individual users rarely distribute their impacts evenly across eventual group paths, they will widen overall impact zones to encompass a zone broader than that of the widest individual user.

Among the inputs, direct resistance to movement through the air might seem irrelevant among practical ground forces, but like internal friction, all power required to overcome it is transferred through the wheels or feet, for they provide the necessary traction. Accordingly, increased frontal area directly affects soils and vegetation, beyond the obvious impacts to trees or shrubs encountered.

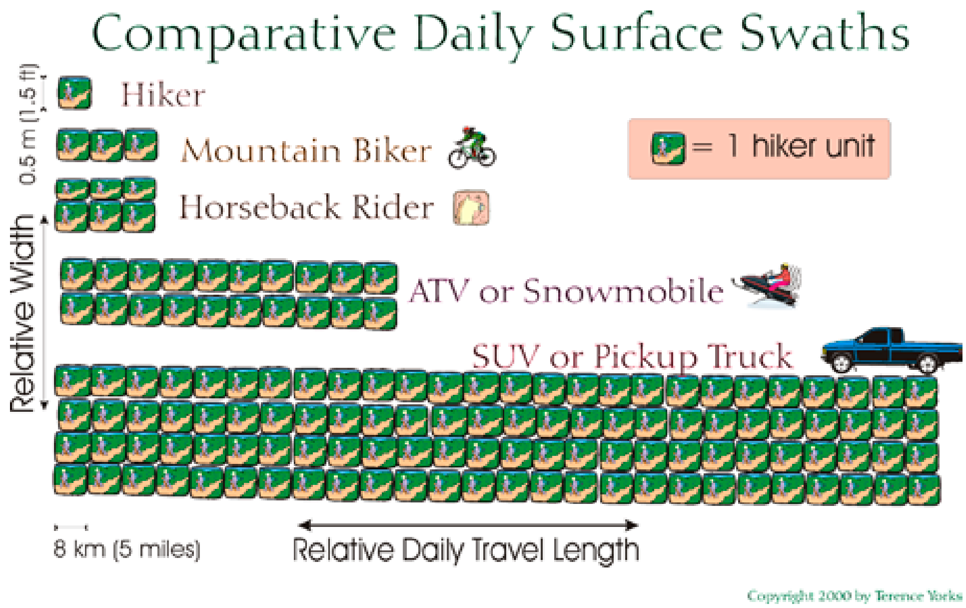
Once again, all consequences tend to apply across user possibilities in direct proportion to the basic parameter.

(4) Length of Travel

Any land user who traverses 100 kilometers of trail in a day will have a correspondingly greater total influence on plants, animals, and soil than another who traverses just 1 kilometer during the same period, even when single encounters may be no different, because there will be so many more of them. Critically, the ease and speed provided by motors, as opposed to muscles, tends to lengthen the average daily use distances very substantially. More formal behavioral studies are needed, but ancillary indications from the database, plus personal monitoring for 40 years across group activities, suggest that open top motorized recreationalists will typically cover more than 10 times the distance during the same land use time as non-motorized users, while closed-cab mechanically assisted operators tend to cover more than 25 times the unassisted daily range.

(5) Swath

The concept of swath effectively combines length of travel with overall user width during passage, and thereby it gives the size of the relative area affected by impact pressure. In one example, a pickup truck is at least three times as wide as a typical hiker. When that minimum truck's width is multiplied by its relative daily range, that product can then compared to a hiker's output, the result becomes a daily swath that increases by more than 100 times as land use changes from walking along trail to sitting in a cab moving over it (Fig. 4).



Integrating Relative User Impacts

The above comparisons suggest that, during an equal time of contact with the land, the simplest statement of any user's impact on soils or vegetation becomes *applied force times the area affected*. In slightly more operational detail, using parentheses to isolate the active components, overall impacts will equal *(the sum of mass and the power applied) over (the width of the path times the distance traveled along it)*. The land use impact summary could alternatively be expressed as *(mass plus power) times (swath)*.

This basic formula for calculating environmental disturbance will necessarily apply most accurately when all other conditions are equivalent. As those conditions vary, it still covers many potential variants surprisingly well. For example, more lasting damage can result from the increased sensitivity of wet or steep soils, but moving across them requires more power to pass through mud or to climb, so the basic equation neatly incorporates these differences.

Refining the various energy inputs to the system further includes many factors that there is no space on this paper to discuss, and then disbursing those forces (e.g., relative mass plus relative acceleration potential) over the relative daily swath area (i.e., width times distance traveled). Empirically testing the possible relationships against the data suggested that the key equation should become, in computer ready format, which could be reduced to abbreviations for traditionalists:

*(Land Use Impact) = ((Mass + (Power / Mass)) * Swath)*

Some of the possible variants and their results are displayed in Table 1, wherein values are rounded to reflect some of their uncertainty.

The most reliable equation demonstrates how a pickup truck user and a hiker are even more unlike than the large differences between their curb weights should suggest. Just one "light" truck will create impacts in daily use equal to those of 4,000 hikers. The equation's integrative calculation projected within Table 1 further suggests that the impact of one bicyclist will be three times that of a single hiker, while a horse will be eight times as great, and a motorcyclist or ATV more than 400 times as much. Further, one of the larger recreational vehicles (RV) will have daily impacts twenty-fold greater than an ATV, and a semi-truck seven times that of the RV. The apparently lessened impact of the army tank arises because, while they have become immensely powerful, their corresponding weight, maintenance, and other limits (e.g., soldiers' ability to withstand the stresses inside them) tend keep tanks in practical use from proceeding very far in a day.

Table 1: Comparative Impacts Among User Types

Category	Mass	Mass	Power	Power	Potential Acceleration	Mass times Power	Mass plus Power	Mass + Acceleration	Daily Range	Daily Range	Width	Width	Net Swath	Net Impact
	kg	relative	kw	relative	relative	relative	relative	relative	km/day	relative	m	relative	relative	**relative**
Hiker	75	1	0.1	1	1	1	1	1	8	1	0.5	1	1	**1**
Bicyclist	88	1	0.1	1	1	1	1	1	25	3	0.5	1	3	**3**
Horse	500	7	1	8	1	53	7	4	25	3	0.8	2	5	**18**
ATV	330	4	15	160	37	690	82	21	83	10	1	2	20	**410**
Pickup Truck	1,800	24	110	1,200	50	29,000	610	37	210	25	2	4	100	**3,700**
Large SUV	2,700	36	150	1,600	44	58,000	820	40	210	25	2	4	110	**4,300**
RV	9,100	120	150	1,600	13	190,000	860	67	420	50	2	5	250	**17,000**
Semi-Truck	36,000	490	300	3,200	7	1,600,000	1,800	250	670	80	2	5	390	**97,000**
Army Tank	55,000	730	670	7,200	10	5,200,000	4,000	370	67	8	4	8	64	**24,000**

Definitions:
relative = compared to one hiker
acceleration = power / mass
swath = range * width
impact = (mass + acceleration) * swath

Discussion

Interpreting the final column of Table 1 should be tempered by appreciating how it represents a midpoint in a set of probabilities. Individual choices can change relative effects, especially on local and particular bases, often dramatically. Among these choices might be visualized a "stupidity factor". For example, a dirt bike easily can be more destructive when run by a person under the influence of excessive machismo than a much more massive vehicle operated by a more restrained citizen. A similar comparison occurs when a large group of hikers cut corners on trails. Hence, from extended observations, stupidity can reasonably be assumed constant across all user classes, which leaves potential impacts varying with weight and power, as the equation suggests.

Cole (1995b) concluded that most plants have a curvilinear response to trampling, so that repeated passes by the same type of user had a reduced effect. Repetitions, like effects of wetness, steepness, and so many others, remain important considerations. While plant impacts may decline with repetition, other impacts (e.g., soil structural damage and erosion) may not. However, the integrating equation presented herein defines the most likely total energy input from all active trampling vectors when all other use factors are equal.

It should maintain its prediction of relative differences across additional particulars of ecological concern, including soil compaction, reduced infiltration, changed plant or animal communities, and accelerated erosion. Exactly how and when each consequence will be expressed can differ greatly with local circumstances, so research into these more detailed factors continues to be valuable and important. Meanwhile, trampling is never the only input to system change.

The motorized classes may well be even more separate from those that operate without assistance from fossil sources than these preliminary inferences from the integrative equation. Petroleum fuels have brought with them a seemingly limitless capability to add weight, power, and range, but their use is anything but without consequence, much of which is cumulative and not immediately visible. Expanses of pavement have allowed those designed for that type of use to extend their ranges even further, albeit at immense environmental cost, which should be attributed to them, but like other issues from air pollution to noise, is even more difficult to specifically enumerate. The currently derived table attempts to correlate the most readily comparable impacts; others are likely to vary similarly.

Most ecologists study details of system function, with arguments invariably following interpretations of their observations, including those with much less potential variability than the present integrating attempt. Experimental ecological science is inherently restrained by the lack of potential for rigorous replication in the natural world, which is just part of the difficulty and expense of conducting effective experiments. Nevertheless, scientific caution from those limits must be balanced by the tendency of vested interests in the status quo to use even apparently unsettled arguments—no matter how individually valid—to rebuff wider scale regulation or change. The problem is how both remaining natural and more disturbed systems are responding by deteriorating more rapidly to continued hesitation either to regulate or to selectively tax impacts resulting from drastically increasing user-brought weight and power.

Even looking back after 15 years from the original draft of this paper, no other studies have appeared with comparable scope to what has been attempted here, with the brief exception following the completion of the core analysis, when the director of the Pennsylvania Transportation Institute reported that one semi-truck "can do as much damage to road surfaces as 10,000 cars" (Pacchioli 1995). That independent conclusion of such a quantitative differential among vehicle classes reflects the conservatism of the calculations in the present analysis. It also confirms that harder road surfaces will be affected in the same manner as soils and vegetation off-roads, since the same forces are involved.

Management Implications

Further revelations of differences among user classes are likely to change numerical particulars, allowing refining the current attempt. Nevertheless, the simplified estimates from the present basic equation should remain useful for quantitative discussion and further experimentation. The basic point should be clearer that differences in impacts between motorized and non-motorized travel—and the differences among types of motorized vehicles—are *much* greater than is commonly assumed, even without considering emotionally debatable insults like noise and toxic fumes. Those, too, with all else equal, will be subsumed into power and weight, for those outputs will inevitably rise in linked step with those basic factors, for they arise directly from them, even if they are altered by mufflers and filters.

Because potential impacts tend to occur eventually in practice, it would seem wise to adjust allowable land uses according to their differential inputs, before the damage from the potential impacts occurs. If restrictions come too late, ecosystem and landscape recovery times may well be estimated by proceeding inversely from the same equation-based framework. The corresponding magnitude of user-group differences should become more important during budgeting and other land management decisions that assess or allocate impact costs or other restraints.

When discussions of equality of user access are entered, the particularly clear differences revealed by daily user swaths seems an excellent place to begin more rational interchanges. Swath could be adopted a useful initial summary term, as the least arguable among user class relationships, allowing practical discussions to begin from how wide the path through the land and how far it extends, with the rest of factors then following. Even changing regulations to reflect swath alone would be a substantial step forward.

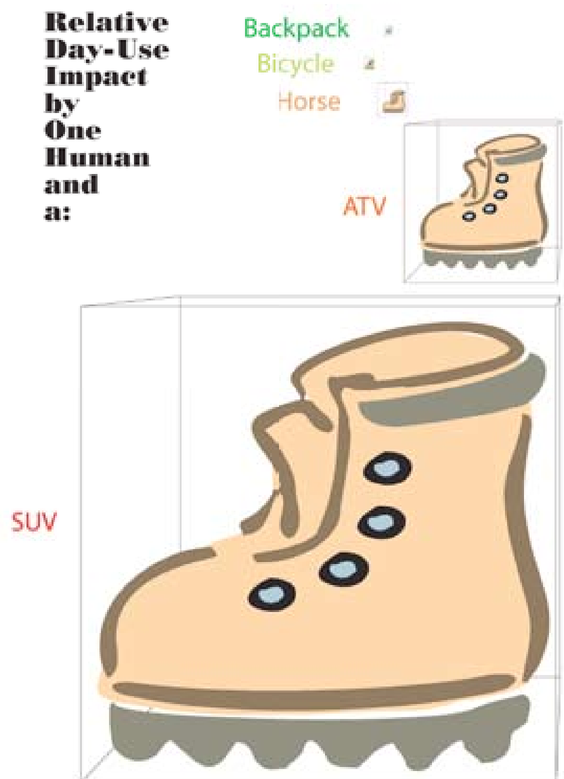
Riders in fossil-fuel-assisted pickups or SUVs weighing 3 tons, or even 250 kg ATVs or snowmobiles, will always remain very different from another person with a 20 kg backpack in what they will do to the landscape as they pass. Equality of opportunity for people is a basic philosophical and legal founding principle of this country, but it still remains to be asked widely whether legal, or practical, equality has ever been intended to apply to machines as well. The latter are, by design, unequal among their own kind, as well as absolutely, inherently unequal in their capabilities to unassisted humans.

Fossil fuels have made a stealth approach into legal philosophy, without a compensating adjustment for just what equality of opportunity ought to mean. Horses first expanded human capabilities, but when steam left them far behind, its use was confined to limited paths defined by narrow steel rails, to wide watercourses. With the automobile, that situation began to change, as expanding capabilities, undertaken by selective choice and underwritten by unequal wealth to purchase them, far exceeded those available more naturally, and coverage by their impacts widely spread. More recently, with widespread manufacture of all-wheel drive alternatives, have similarly large capability differences to be dispersed almost everywhere. Exponentially expanding human populations, but static land resources, compound all relative use issues.

Conclusion

If equality should be for human individuals, the equation derived above can provide a significant clue for assessing allocations among limited spaces and competing access rights. Changing ongoing arguments from whether all users should be allowed access on a basis of presumed equality without question of impact consequent likelihood upon others and the landscape, to how much different those impacts are likely to be, based upon how much different users become by their choices of what to bring to the land with them, could begin to bring rationality to a currently almost strictly arbitrary, emotional debate.

The equation presented herein offers a quantitative way to comparatively project impacts created by each human land user on an equal-time-of-use basis, which can be visualized in Fig. 5. From it, managers can more accurately project compensating costs and/or restraints, and then present them in a more readily believable context. Exactly how much different users are likely to become by their own active choices, as opposed to their internal capabilities, may be extrapolated from the suggested equation as well. It is becomes a starting point to begin replacing not even trying to consistently enumerate differences, which extend so much further than those envisioned by this nation's founders, or their ongoing ideals. If wider acceptance follows, that should create both more equitable, more sustainable land access, on a per-human opportunity for equal area and effects basis, thereby with the possibility for lessened conflicts and consequences from active land use. Overall impacts, whether on public or private land, will diminish in direct proportion to any and all reductions to the total weight, power, width, and/or distance traveled, with much more dramatic potential for improvement among externally fueled mechanical devices, since these are currently so much heavier and powerful than humans.



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