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Investigating feedbacks in human–landscape systems: Lessons following a wildfire in Colorado, USA

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ABSTRACT

As human interactions with Earth systems continue to intensify, understanding the complex relationships among human activity, landscape change, and societal responses to those changes becomes increasingly important. Interdisciplinary research centered on the theme of "feedbacks" in human–landscape systems serves as a promising focus for unraveling these interactions. This paper examines the specific case of the 2012 Waldo Canyon Fire of Colorado, where human responses after the fire to perceived threats of hydro-geomorphological hazards included construction of tall fences at the base of a burned watershed. These actions prompted feedbacks that promoted further landscape change that ultimately increased those hazards, rather than dampening the hydro-geomorphological effects of fire. Geomorphic analysis showed that the fences trapped particles that would naturally move through the system by flows with recurrence intervals greater than 3.3 years. With the particles blocked by the fences, the channel downstream became erosive, because it was devoid of large particles that produce substantial hydraulic resistance. Channel incision prompted a second human response to pave the eroding channel, which led to further incision downstream. This cycle of positive feedbacks between human decision-making and landscape change eventually led to a complete channelization of the stream channel downstream of the fences. The explanation for the transformation of the post-fire landscape therefore lies in the interacting human impacts and feedbacks, rather than the expected post-fire hydro-geomorphological adjustments. An initial agent-based model, capable of integrating social and hydro-geomorphological data, simulates these interacting impacts and feedbacks. Further refinement with more complete data input, especially pertaining to human decision making at individual or local levels, is required to fully demonstrate the utility and promise of this tool for application to geomorphic analysis.

1. Introduction

Human interactions with Earth systems have intensified in recent decades, causing changes in landscapes almost everywhere and in every way. With a human population continuing to grow, these changes are expected to magnify, with direct and indirect consequences for human society. Recognition of the significance of these changes has prompted new terms and concepts to emerge in the scientific literature. They include "Anthropocene" (Crutzen and Stoermer, 2000) to denote a new time-frame dominated by human activity, and anthropogeomorphology (Cuff, 2008) to represent an invigorated focus on the study of a geomorphology of human activity (Jefferson et al., 2013). New journals have also surfaced to advance knowledge of human interactions with Earth systems (Chin et al., 2013), another reflection that the times are no longer the same. A strong need exists to accelerate scientific research to understand, predict, and respond to the rapidly changing processes on Earth. These processes include the increasing complex and multi-layered interactions and feedbacks within a system context (Chin et al., 2014).

Collectively, the research community is responding to grand challenges (NRC, 2010, 2012) that call for explicit consideration of human activity in understanding and anticipating Earth's changing surface into the future. Meeting these challenges requires development and application of new conceptual frameworks and integrating methods linking a broad range of sciences (Chin et al., 2010). New questions should address not only the human impact on Earth's surface systems, following a traditional emphasis (e.g., Goudie, 2006), but also the interacting human responses to landscape change. In this context, "feedbacks" has been identified recently as a promising theme for interdisciplinary research (Harden et al., 2014; Wohl et al., 2014). For

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example, how can we identify feedback loops and potentially alter them to slow or reverse degradation, even where coupling is indirect, diffuse, or weak, or where they involve threshold dynamics — within geomorphic and/or human systems? How, when, and where are feedback mechanisms triggered by interactions among geomorphologic, ecologic, climate, and human systems?

Despite the fact that understanding feedbacks in human–landscape systems is germane for advancing knowledge of Earth's evolving surface into the future, key challenges exist for geomorphologists (Chin et al., 2014; Harden, 2014). These challenges center on how to quantify and model the dynamics of the many diffuse and potentially weak feedbacks that occur through diverse systems across varying time and space scales. In linking the human impact with response, much more capability exists (i.e., data, knowledge, tools) to quantify human impacts on geomorphological processes than the human responses to those alterations. In turn, less is known about how human responses change the reference (initial) conditions of the system that existed before human impact.

In addition, quantifying and linking processes that span geomorphological and human systems over diverse space and time scales require development and application of new analytic tools. In this context, agent-based models (ABM; Zvoleff and An, 2014) offer a new tool for incorporating human behavior and decision-making for the study of Earth's surface dynamics. These models could potentially overcome limitations of empirical methods while integrating human and geomorphological processes (Wainwright and Millington, 2010; NRC, 2012). Yet, geomorphologists have only begun to explore the use of ABMs. Difficulties with identifying and conceptualizing the interacting feedbacks and with adequately quantifying the vast array of physical effects and human or ecosystem responses limit the wide use of such models. Nevertheless, ABMs have successfully simulated human-induced changes along coasts (e.g., McNamara and Werner, 2008) and policy-driven alterations within forests (e.g., Soares-Filho et al., 2006). An urgent research need includes applications that effectively demonstrate how feedbacks between human and physical systems can be studied, both conceptually and methodologically (Chin et al., 2014).

In this paper, we address this need by providing an example of feedbacks between human and fluvial landscape systems precipitated by a recent wildfire in Colorado (USA). First, we highlight the significance of feedbacks in human–landscape systems by briefly reviewing definitions and linkages. Next, we outline the case of the 2012 Waldo Canyon Fire, focusing on the human responses after the fire that prompted feedbacks in the human-geomorphic systems. Third, we report quantitative and qualitative analyses of geomorphic and human–social processes involved in the human impact and response loops. Fourth, we show how the human-landscape interactions can be conceptualized in an agent-based model and explore its utility with preliminary data. Finally, we discuss continuing challenges and opportunities for advancing knowledge of feedback interactions in human–landscape systems, including next steps toward quantification using ABMs.

2. The significance of feedbacks in human–landscape systems

Feedbacks occur within Earth's systems in the absence of human influences. A positive feedback is a change in a system that in turn causes more change in the same direction. In a glacial system, for example, a growing glacier with an enlarging white surface will have higher albedo, thereby reflecting greater amounts of solar radiation and facilitating the further growth of the glacier (Hall, 2004). Similarly, a melting glacier may cause the ice to slide at the base because of the lubricating effect of the meltwater. The sliding, in turn, may cause greater friction, generating more heat and ultimately, more melting (Oerlemans, 2013). Positive feedbacks are therefore self-enhancing processes that typically cause instability within systems. In contrast, a negative feedback is a change that prompts an adjustment that limits or counters the initial change. Negative feedbacks are self-regulating mechanisms that provide stability within systems. For example, as the process of urbanization increases runoff into river channels, the greater water discharge typically erodes channel beds and banks to create larger channel cross sections. These enlarging channels, in turn, would ultimately limit channel erosion by reducing velocities (and therefore boundary shear stress) in the water flows (Morisawa and Laflure, 1979; Chin, 2006).

Feedbacks involving human influences modify Earth's surface processes in similar ways. Positive feedbacks occur where human actions induce change in the same direction, leading to instability. For example, in the Colorado Front Range where prolonged and intense rainfall during September 2013 caused widespread flooding, floodwaters caused extensive bank erosion and introduction of large amounts of coarse wood into stream channels. If left in place, instream coarse wood can effectively reduce continuing channel erosion – i.e., promote a natural negative feedback cycle – by dissipating flow energy (Keller and Tally, 1979; Curran and Wohl, 2003). This process creates localized flow separation that enhances sediment storage in the zone where flow decelerates (Brooks et al., 2003; Faustini and Jones, 2003). It also facilitates overbank flows that result in lower instream velocity and sediment deposition on the floodplain (Wohl, 2013). Because people generally perceive instream coarse wood as undesirable and unnatural (Chin et al., 2008), flood-recruited wood is often quickly removed from channels, as was the case throughout the areas affected by the 2013 flooding. This human action can trigger a positive feedback that promotes post-flood erosion because of a lack of hydraulic resistance within stream channels. Without the benefits of wood in stream channels, continuing bank instability and channel erosion occurred during the 2014 snowmelt peak flows. The human response of removing wood, therefore, likely exacerbated the original hazards caused by the 2013 flood.

Negative feedbacks involving human responses are significant in offering potential to slow, minimize, or reverse the impacts of human activity (Walker et al., 2004; Chapin et al., 2006) because they produce change that limits or counters the initial impact and promote stability within systems. Human activities have impacted the dissected loess and till plains of north-central Kansas and southern Nebraska, for example, including agricultural practices, channel straightening, and removal of riparian vegetation. These activities have triggered widespread channel incision of more than five meters over the past five decades. Although the incision could not be stopped, subsequent channel widening served to dissipate the erosive energy of stormflow and encouraged deposition of sediment (Simon and Rinaldi, 2006). Thus, a negative feedback ultimately facilitated the reversal of the initial direction of downcutting.

Although the qualitative examples cited above illustrate feedbacks involving human activity, causal linkages are difficult to identify, quantify, and predict. Human processes introduce behavior and decision making, as well as a wide range of social issues that sometimes originate from faraway places (Chapin et al., 2006). Such interactions can also occur on top of complex Earth surface dynamics that themselves might exhibit feedbacks. Because both positive and negative feedbacks can operate in the same human–landscape system, sometimes changing direction when a system crosses a threshold (Florsheim et al., 2013), deciphering which feedback may dominate at a given time is especially challenging. Feedbacks precipitated by the Waldo Canyon Fire, outlined below, provide a timely example of identifying feedbacks between human and geomorphic processes and attempting to capture these feedbacks within the framework of an agent-based model.

3. The 2012 Waldo Canyon Fire of Colorado

3.1. Background

The Waldo Canyon Fire was one of several wildfires that burned during the dry summer of 2012 on the Front Range of Colorado. Ignited on 23 June 2012, the fire was contained on 10 July 2012 after burning 74 km^2 of land. The burn occurred mostly in Pike National Forest,

approximately 8 km northwest of the city limits of Colorado Springs (Fig. 1). About 19% of the burn was classified as high severity, 40% moderate severity, and 41% low severity (Young and Rust, 2012). The size of the burned area was modest compared to other fires in Colorado's history. For example, the Hayman Fire of 2002 scorched 559 km^2 (e.g., Lewis et al., 2006), whereas the High Park Fire that also burned in 2012 charred 353 km^2 of land.

What stands out about the Waldo Canyon Fire, however, is its high social impact because of its close proximity to Colorado Springs and other communities. The fire forced the evacuation of more than 32,000 people, including 22,000 residents within a two-hour period on 26 June 2012 (City of Colorado Springs, 2013). It damaged 346 homes, mostly in the Mountain Shadow neighborhood (Fig. 2), and killed an elderly couple. These homes were downslope of a major topographic ridge that normally would have kept the fire from spreading. Erratic winds exceeding 100 km per hour, fueled by dry conditions, caused the fire to cross the ridge into the residential neighborhood. Insurance claims from loss and damage from homes alone totaled $353 million. Loss of businesses would tally many more millions of dollars. In addition, the U.S. Forest Service reportedly spent ~$13 M fighting the fire. The city of Colorado Springs also recorded over $4 M in overtime wages during and after the fire. Colorado Springs Utilities further spent more than $2.7 M restoring utilities. These figures are only initial estimated costs of the fire, as secondary effects are expected to continue, including post-fire flooding and efforts to mitigate and treat such effects. Considering these diverse and significant costs, the Waldo Canyon Fire was the most expensive fire in state history at the time (Wineke, 2012).

3.2. Human impact and responses

The high degree of human interaction during and after the fire makes the Waldo Canyon Fire an ideal case for examining human–landscape feedbacks. In the first instance, human activity caused the fire (Parker, 2012). Thus, a human action was the first trigger of the chain of complex and layered interactions that followed (Fig. 2; Human Action #1). Wildfire typically brings on a suite of hydrologic and geomorphologic effects, changing the landscape until these effects dampen over time. These changes include decreased infiltration and soil water repellency, leading to elevated runoff, soil erosion, and altered sediment transport and channel morphologies (Moody et al., 2013). These changes are observed in the area burned by the Waldo Canyon Fire. From a fluvial systems viewpoint, many adjustments may take place within a drainage basin in response to a perturbation brought on by fire (Fig. 2). These interacting adjustments themselves likely involve feedbacks. The process of adjustments toward a possible new equilibrium, albeit not exactly the pre-fire state, is often viewed as the "recovery" of the system.

In the case of the Waldo Canyon Fire, human actions during and after the fire would further impact the post-fire effects and adjustment processes. Human intervention on natural processes began during fire (Fig. 2; Human Action #2) with retardants sprayed from the air to suppress fire and contain its spread. Management responses during the Waldo Canyon Fire also involved dropping straw and wood chips from helicopters to inhibit post-fire erosion. Subsequent treatments on-the-ground (Fig. 2; Human Action #3) included installation of erosion barriers and sediment basins, as well as direct manipulation of river channels. The manipulation of hillslopes and channels was intended to dampen the effects of fire (i.e., inhibit landscape change) by retarding erosion and movement of water and sediment down barren hillslopes and through river corridors. Because of residential communities downstream, these and similar attempts to mitigate post-fire hazards are often high priority to alleviate immediate human concerns. Yet, the effectiveness of these efforts is unclear (Napper, 2006; Robichaud and Ashmun, 2013; Robichaud et al., 2013), leading to questions of the ultimate impacts of these further cumulative

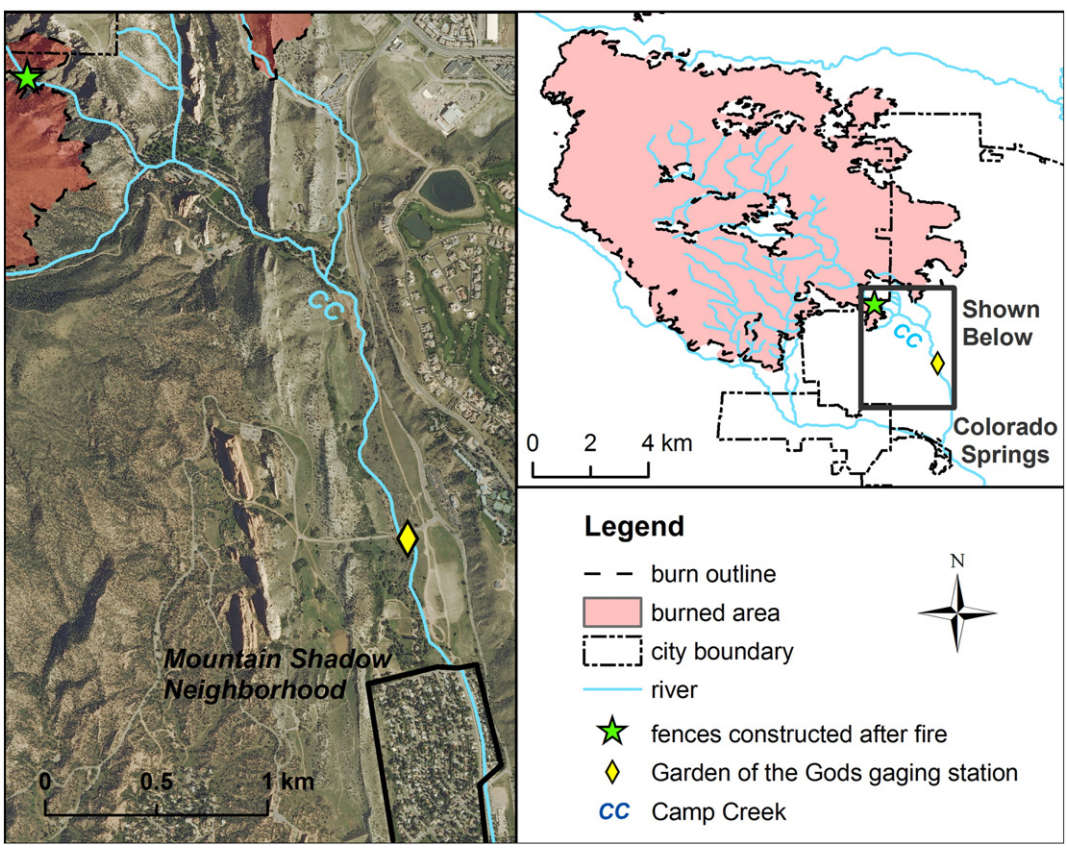

Fig. 1. Location of Waldo Canyon Fire.

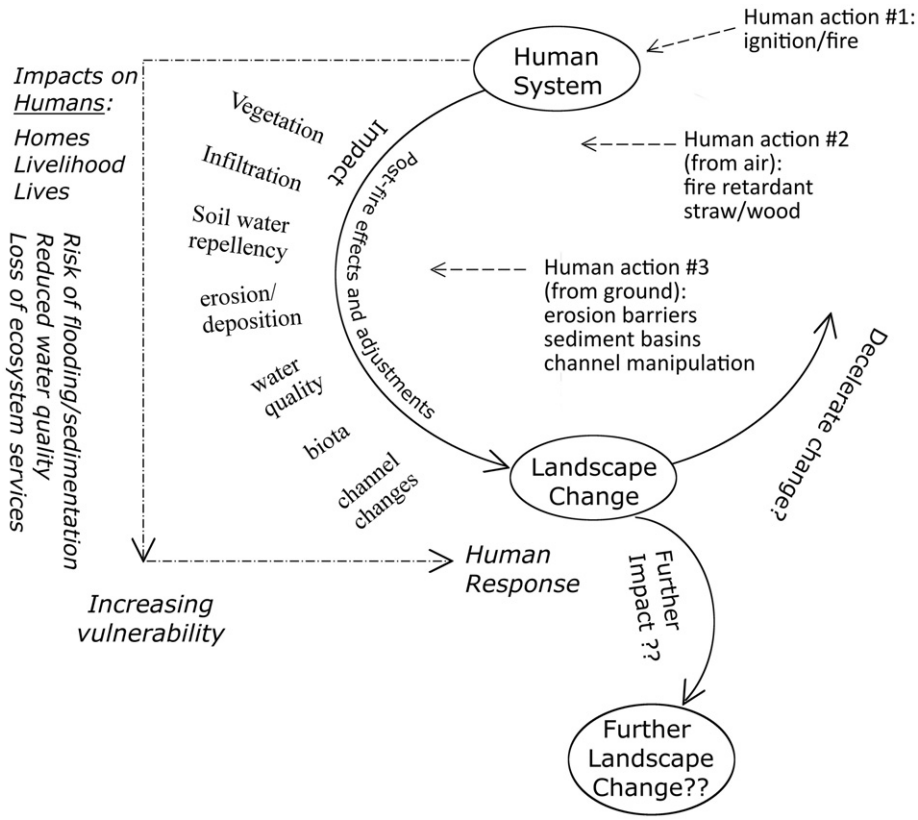

Fig. 2. Feedback interactions between human and fluvial landscape systems following the Waldo Canyon Fire.

human activities on a landscape that is already changing. Human interventions mask the magnitude of post-fire effects and confound causal connections, making predictions of change difficult (Gresswell, 1999). Human manipulation of burned landscapes also affects the cycle of natural recovery within ecosystems, many of which have demonstrated a remarkable resilience without human intervention (e.g., Yellowstone after the 1988 fire; Romme et al., 2011).

Superimposed on the natural post-fire changes in the landscape, some of which are additionally influenced by human actions, is the direct toll of the fire itself on humans (Fig. 2; left side of diagram). Direct consequences of the Waldo Canyon Fire included loss of homes, livelihood, and even lives. Other impacts included post-fire risks of flooding, sedimentation, and reduced water quality. After wildfires, nutrient loadings and metal concentrations in streams typically increase from the burning of organics, along with sediment-laden floods (Ranalli, 2004; Mast and Clow, 2008; Burke et al., 2013). Therefore, the loss of ecosystem services and risks associated with post-fire effects often leave residents feeling vulnerable (Simon, 2012). As homeowners move out of burned areas, attrition also impacts residents' sense of community and well-being (McGee and Russell, 2003; Carroll et al., 2005). The increasing vulnerability of communities, in turn, often prompt human responses that further trigger additional feedback interactions, promoting or inhibiting further landscape change (Fig. 2).

3.3. Human response to the Waldo Canyon Fire: the case of the tall fences

One such human response to the Waldo Canyon Fire was the construction of two tall fences at the mouth of the Camp Creek watershed (Figs. 1 and 3). Private citizens built these fences in Spring 2013, in anticipation of the first post-fire season of summer storms, which they feared might trigger flooding and debris flows. Both fences are 6.4 m high with two layers of openings: a set of larger rings of approximately 30 cm in size, and a smaller mesh with openings of 11.3 cm (Fig. 3b). The smaller, flexible ring nets help the fence withstand high static and dynamic loads (Geobrugg, n.d.). Support ropes on both sides of the fence are intended to reduce the impact of debris by transferring the pressure load to the ground (KANE GeoTech, Inc., 2012). The upstream fence is ~21 m wide at the top and ~15 m wide at the bottom (Fig. 3a). The downstream fence, ~25 m wide at the top and ~12 m at the bottom, was designed to accommodate an adjacent utility road for routine maintenance (Jordan, 2013). The two fences are spaced approximately 400 m apart and are expected to remain in place for at least 8 years (Strickler, pers. comm., 2012). Together, they are intended to trap sediment and debris from reaching the base of Camp Creek, thereby protecting communities downstream.

Constructing fences and other similar structures is undertaken to minimize threats to property and lives. Yet, these structures also clearly affect the movement of material and the overall functioning of the fluvial system, and are not without their own risks. They also raise the question of how such additional human actions might affect the geomorphic adjustments taking place that are already coupled to human activities and responses (Fig. 2). To understand the feedbacks triggered by the installation of the fences, and to explore how to quantify and simulate such interactions, we next outline the decision-making processes that led to the construction of the fences. Then, we use geomorphic analysis to examine how the fences affect channel morphology and sediment transport through the river system. Finally, we develop a simple agent-based model to simulate and capture the coupled human-geomorphic feedback interactions.

4. Human decisions, geomorphic changes, and feedback interactions

4.1. Decision making

Studies conducted in the aftermath of the Waldo Canyon Fire influenced the decision to construct the tall fences. The U.S. Geological Survey (USGS) and the Coalition for the Upper South Platte (CUSP) determined risks associated with potential flooding and debris flows

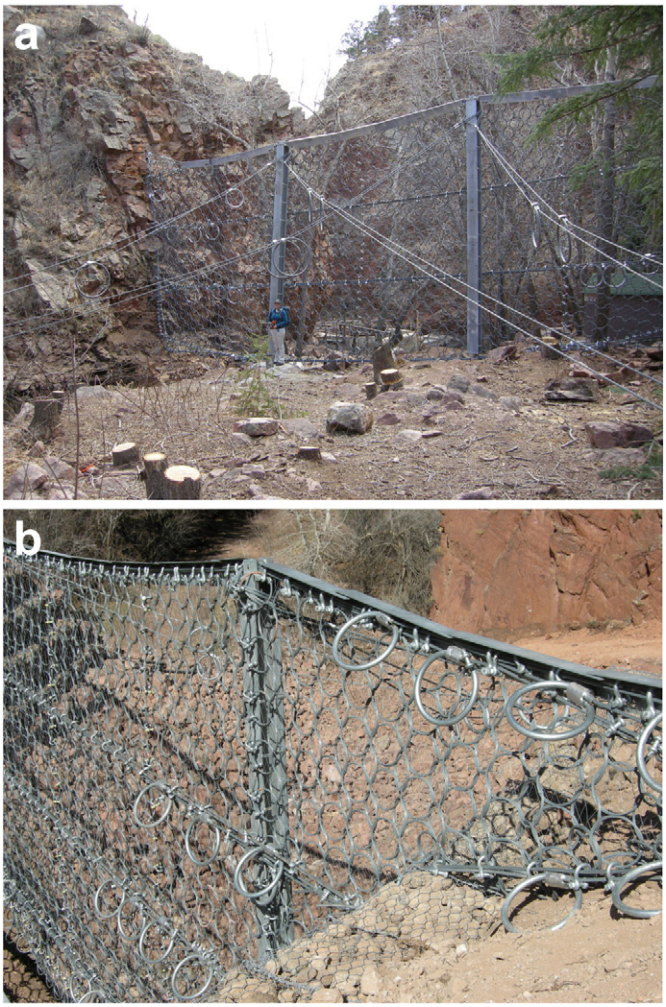

Fig. 3. (a) Upper fence with person for scale; (b) Fence showing rings and smaller mesh with 113 mm opening. Photos taken 7 April 2013.

in areas downstream from the burn area (Verdin et al., 2012; Young and Rust, 2012; Rosgen et al., 2013a). Based on predicted debris flow probabilities and volumes of potential sediment delivery from burned watersheds, the USGS assessment indicated "a potential for substantial debris flow impacts on buildings, reservoirs, roads, bridges, and culverts located both within and immediately downstream from the burned area" (Verdin et al., 2012; page 1). Similarly, the CUSP post-fire study identified the Camp Creek watershed at risk for floods and debris flows. According to the study, a 10-year storm within Camp Creek posed a 45% probability of generating debris flows of 100,000 m^3 or more, a volume far larger than any other watershed examined (Verdin et al., 2012).

Camp Creek flows through several private and public properties before emptying into Fountain Creek in the city of Colorado Springs (Fig. 1). Based on the studies of potential flooding and debris flows, the private land owners feared that future storm events could trigger high volumes of water and debris flowing onto the local properties. Within a few months of the fire, they initiated discussions with public agencies and consultants to develop hazard reduction plans that would protect their property from these perceived threats (Strickler, pers. comm., 2014).

The local land owners contacted a geotechnical engineering firm to conduct a formal assessment of engineering options for hazard reduction. The firm felt that installations, such as barriers and diversions made of burnt trees and boulders, were not viable due to the bedrock character of the channels. The engineers also felt that excavation of channel and sediment catchment basins, often used by the U.S. Forest Service (USFS; Rosgen et al., 2013b), were unsuitable because the geologic conditions of the area would present challenges for engineering and maintenance. The final recommendation, therefore, was to build aboveground large fence barriers or "debris racks" at two locations near the mouth of Camp Creek. The fences were constructed at a cost of about $616,000.

4.2. Geomorphic analysis

To understand how the fences affect geomorphic processes, we focus on the following questions:

- Given the size-range of the particles trapped by the fences, what ranges of flows affect sediment dynamics? In other words, do the fences block sediment transported by essentially all but the smallest flows? Or, are only the largest flows affected, such that the majority of the sediment load is still moving through the system?
- What are the predicted and realized channel changes downstream of the fences as a result of sediment trapping by the fences over the scale of one storm season?

4.2.1. Frequency of impact on sediment transport

To address the first question, we use Shield's Eq. (1) to calculate the critical shear stress needed to entrain the largest particle that can move through the fence opening of 11.3 cm.

$$\tau_{cr} = \tau_{ci} * g(\rho_s - \rho_w)d \tag{1}$$

where, τ_{cr} = critical shear stress; τ_{ci} = dimensionless critical shear stress (0.06); g = acceleration of gravity (9.807 m/s^2); ρ_s = particle density (2650 kg/m^3); ρ_w = water density (1000 kg/m^3); d = median particle diameter (0.113 m, the size of the opening of the fence). This calculation resulted in a value of τ_{cr} = 109.7 N/m^2.

To calculate the range of flows that influence sediment dynamics, we then determine the discharge needed to exert the critical shear stress for sediment transport. The Duboys (2) and Manning (3) equations yielded the hydraulic radius and velocity, respectively, of the flow capable of entraining particles of median diameter of 113 mm (11.3 cm).

$$\tau_0 = \gamma R s = \tau_{cr}; \text{ therefore } R_{cr} = \tau_0/\gamma s \tag{2}$$

$$V_{cr} = \left(R^{2/3} s^{1/2}\right)/n \tag{3}$$

where τ_0 = boundary sheer stress (set equal to critical shear stress; must exceed the critical value to entrain particles, (corresponding to the fence openings) with median diameter of 113 mm median diameter); γ = specific weight of water (9810 N/m^3); R = hydraulic radius (m); s = slope (0.04; from field survey); V = velocity (m/s); n = Manning's coefficient (0.07 for mountain stream with cobbles and large boulders; Chow, 1959). These equations yielded a hydraulic radius (R) of 0.28 m, with a corresponding velocity (V_{cr}) of 1.22 m/s.

Field surveys of a representative channel cross section at the fences provided the critical cross-sectional area (A_{cr}) corresponding to the critical hydraulic radius (R_{cr}; Eq. (2)). This area (A_{cr} = 1.5 m^2) allowed determination of the critical discharge (Q_{cr}) necessary for entraining particles with diameter of 113 mm, which was 1.83 m^3/s (65 ft^3/s):

$$Q_{cr} = A_{cr} V_{cr} \tag{4}$$

Lastly, we determine the recurrence interval of this critical discharge with a frequency analysis (step 5). For this procedure, we used flow records for a gauging station on Camp Creek ~2.5 km downstream of the fences (Station 07103703; Garden of the Gods, CO). No tributaries

join Camp Creek within this stretch of channel between the lower fence and the gauging station. Therefore, streamflow records at the gauging station provide useful data for approximating the recurrence intervals of flows at the fences. A frequency–magnitude analysis of the annual peak discharges for the 21-year record (Table 1) produced a recurrence interval (R.I.) of 3.3 years.

These results suggest that flows with recurrence intervals of approximately three years are capable of moving particles equal to the sizes of the openings in the fences. That is, as long as the flows are small, with a R.I. less than ~3.3 years, the fences do not affect sediment transport. But they will impact larger flows with R.I. greater than ~3.3 years that are capable of mobilizing coarser material. At these larger flows, the fences are expected to trap particles that otherwise would be transported downstream into the study reach and beyond.

4.2.2. Downstream changes in channel morphology

To document channel changes downstream of the fences, we conducted field surveys at a study reach immediately below the lower fence (Glen Reach Below Fence) at selected time intervals. An automatic level and stadia rod provided elevation data for longitudinal profiles and cross sections. Particle-size measurements included pebble counts (after Wolman, 1954) and the intermediate axis of particles comprising steps (after Chin, 1999). Repeat photographs further characterized the channel morphology. These field surveys tested the hypothesis that degradation would occur in the channel reach downstream of the fences. Because of scouring and degradation from a "hungry water effect", this process is analogous to the effects downstream of dams, where flows devoid of coarse particles become more erosive (Kondolf, 1997).

The field measurements produced results as hypothesized, along with a few surprises. The longitudinal profile on 13 July 2013 below the downstream fence (Fig. 4) represents the channel morphology largely unaffected by the fences; the fences were built during a dry period just a few months before this date. The flows of summer and fall 2013, however, included several events exceeding the critical discharge for transport of coarse sediment greater than the size of the openings in the fence (1.83 m^3/s). These flows occurred on 9 August with a peak of 6.54 m^3/s, as well as during the period of 11–14 September in response to prolonged and intense rainfall events. These precipitation events also produced major flooding along other areas of the Colorado Front Range (Gochis et al., 2015). Although peak discharges at the Camp Creek at Garden of the Gods, CO gauging station (Station I.D. 07103703) are not available for 12–14 September 2013, the gage recorded an instantaneous peak value of 3.23 m^3/s on 11 September, and mean daily discharges of 3.99 m^3/s, 6.14 m^3/s, and 2.97 m^3/s for 12, 13, and 14 September, respectively. The gage also registered a peak discharge of 1.93 m^3/s on 17 September 2013. These flows, therefore, had capacity to transport particles larger than 113 mm median diameter into the study reach downstream of the fences. The movement of particles of this size if now blocked, however, by the fences (Fig. 5). By the following spring (21 March 2014), the surveyed profile showed degradation of the channel bed by nearly one meter (Fig. 4).

These results suggest that the fences have an unintended consequence of facilitating erosion downstream, even though they may stop large objects from causing other damages. Further, as coarse particles that are present downstream of the fences are transported down the basin and are not replaced by materials upstream, the channel loses roughness elements that promote energy dissipation in the mountain fluvial system. Over time, decreasing roughness should lead to even higher erosive capacity. Devoid of coarse particles, the channel may also change from a step-pool morphology (Fig. 6) to a plane bed over time.

Table 1
Annual peak discharge at the Garden of the Gods gauging station.

Year	Date	Peak discharge (m^3/s)
1992	June 5	0.08
1993	March 29	0.03
1994	September 2	7.73
1995	May 30	4.11
1996	July 9	0.08
1997	June 6	6.17
1998	July 30	3.17
1999	April 29	12.18
2000	August 31	0.04
2001	August 31	0.26
2002	May 16	0.03
2003	May 24	0.08
2004	July 16	0.28
2005	June 11	0.09
2006	June 25	0.34
2007	May 9	0.62
2008	June 20	0.10
2009	July 2	0.17
2010	April 26	0.40
2011	July 2	0.26
2012	July 30	8.64

4.2.3. A continuing feedback cycle

Because of the incipient erosion downstream of the fences, a decision was made by March 2014 to pave the eroded segment of channel immediately downstream of the lower fence (Fig. 7a). This decision represented another human response to the erosion triggered by the first decision to install the fences, and by the subsequent unintended effects of the fences. The pavement will certainly inhibit erosion locally, but it will also further decrease roughness, thereby increasing velocity and erosive capacity downstream. Such erosion was already evident in the surveyed longitudinal profile of 21 March 2014 (at approximately 55 m where the pavement ends; Fig. 4). The continuing erosion downstream of the paved area prompted yet another decision to ultimately fill and channelize the entire creek below the lower fence (Figs. 7b and 8), thereby connecting it to the urban concrete channel farther downstream in Colorado Springs. The initial decision to construct the fences therefore ultimately determined the fate of the channel downstream. Although the decision was a human response to the threats of post-fire geomorphological hazards, the transition to the urban channelized stream from its previous natural state was, in the end, not a direct geomorphic consequence of wildfire. The human decision to construct the fences had the unintended consequences of promoting further landscape change in a positive feedback loop (Fig. 2).

4.3. Capturing feedback interactions with agent-based models

To capture these feedback interactions, we built an agent-based model (ABM) to simulate geomorphological changes interacting with human intervention in the fluvial system, in this case fence building and channel paving downstream. The model applies simple rules and assumptions while retaining a physical basis, to demonstrate the use of ABMs in geomorphological research, as well as some of the technicalities involved. The rationale for selecting the agent-based modeling approach was to demonstrate a framework that could be used to examine feedbacks between human decisions and physical processes (An, 2012; Zvoleff and An, 2014). We quantified changes in channel degradation using a simple algorithm with the field data described above to inform the model.

In this ABM, we conceptualized a 70 m study channel reach as a linear feature comprised of 70 connected linear segments, with each segment 1 m long (Fig. 9). Each segment is considered an agent or object in the model. Each segment agent has several key attributes: the elevation of the subsurface bedrock, the thickness of the alluvial sediment layer overlying bedrock, and the average elevation of the channel segment that equals the bedrock elevation plus sediment thickness. Assuming that the elevation of the subsurface bedrock is constant over the timespan of the study, the elevation of the channel segment

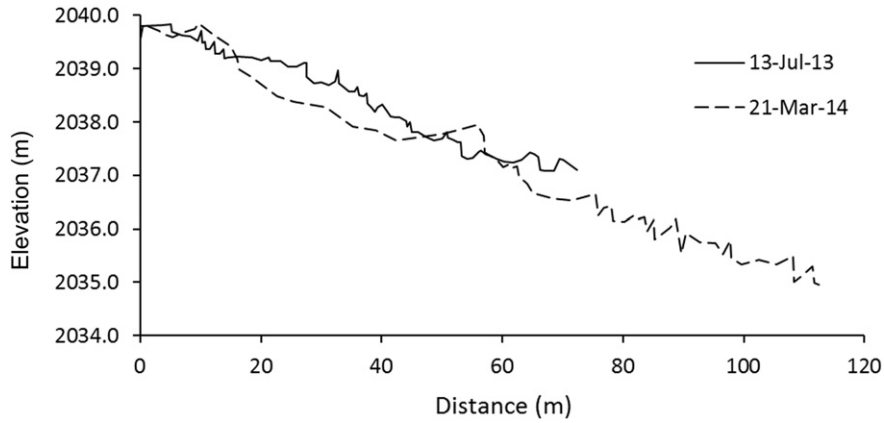

Fig. 4. Longitudinal profile of study reach below fences: 13 July 2013 and 21 March 2014.

corresponds to changes in the thickness of the sediment layer. If t_o is the current time, and Δt is the elapsed time, then at any time $t + \Delta t$ the elevation of the channel segment is

$$E(t + \Delta t) = E_{bedrock} + E_{sediment}(t) + Rc(t) * \Delta t \quad (6)$$

where $E(t + \Delta t)$ is elevation of the surface at time $(t + \Delta t)$, $E_{bedrock}$ is elevation of the bedrock, $E_{sediment}(t)$ is thickness of sediment at time t, and $Rc(t) * \Delta t$ is the rate of change in the thickness of sediment from time t to $(t + \Delta t)$.

The main task was to simulate the change in the thickness of the sediment layer, i.e., Rc(t), which depends on sediment transport affected by construction of the fence. For smaller flows that mobilize sediment less than 113 mm in diameter (the size of the opening of the fence), we assumed that the transported sediment in the study reach below the fence is replenished by materials from upstream moving through the fence. The net change in sediment thickness under this scenario is zero. For flows capable of mobilizing particles greater than a median diameter of 113 mm (the size of the opening of the fence; Eqs. (2) to (4)), those particles are blocked by the fence. Below the fence, because particles that are transported downstream are not

Fig. 5. Upper fence blocking particles from transport downstream. Photos taken 3 October 2013.

Fig. 6. Channel character downstream of lower fence before construction.

Fig. 7. (a) Paved channel bed and banks extending ~60 m downstream of lower fence, 21 March 2014; (b) Channelized reach downstream of lower fence, 9 August 2014.

replaced, sediment thickness decreases. We set this decrease as a minimum amount equivalent to 113 mm, the median diameter of one particle mobilized and transported from the downstream area. For flows with shear stresses exceeding the critical value for the movement of the step particles present in the study reach (230 mm), we set the decrease in the thickness of sediment as 230 mm. Similarly, this amount of decrease corresponds to the median diameter of one particle mobilized that is not replaced from upstream.

The model interrogates the flow record at 15-minute time steps to determine the movement of sediment and changes in bed elevation, using the following preliminary rules:

1. If flow <1.83 m^3/s, no net change in sediment thickness (surface elevation) occurs.
2. If 1.83 m^3/s < flow < 8.8 m^3/s: For each 15 min interval during the day that 1.83 m^3/s < flow < 8.8 m^3/s, sediment thickness decreases by 0.113 m from the most upstream segment.
3. If flow >8.8 m^3/s, sediment thickness decreases by 0.230 m from the most upstream segment.
4. Once the first segment erodes to bedrock (i.e., sediment thickness decreases to 0), the next downstream segment begins to decrease in sediment thickness (erode) following the rules above.
5. Once paving occurs, the bedrock elevation of the affected segments increase to a level determined from empirical data, and the corresponding sediment thickness becomes zero.

NetLogo provided a freely available software package for coding the ABM (Fig. 9). We set t to 0 (the initial time) to represent the time that the fence is built, the first human response. To represent the second human response (the channel paving), we reset the sediment thickness to zero ($E_{sediment}(t) = 0$) while raising the elevation of the bedrock ($E_{bedrock}$), as outlined in rule 5. To represent these aggregate level human decisions, we set an observer-level agent (corresponding to system manager or policy maker) and represent his/her decisions in the ABM about whether to build a pavement and if so, when to build it. The two bars in Fig. 9, named "build-pavement?" and "pave-time?", represent these decisions, respectively. The other two bars in Fig. 9 are other observer-level agent decisions: time span of the simulation (the bar "Simu-time") and the way sediment thickness may change in response to flow changes (the bar "Sediment-chg-order"; Fig. 9). The time span can be set as high as 400 steps (days; adjustable to any number of interest). The default for the change in sediment thickness change follows the preliminary rules outlined above (i.e., when the "Sediment-chg-order" bar is set at "on"). When the "Sediment-chg-order bar" is set at "off", the thickness of all segments decreases simultaneously at a rate determined by rules 1–3 until it becomes zero (this option is primarily for the purpose of testing the model). To test the ABM, we compared the predicted segment elevations at discrete time steps with the March 2014 survey following the model verification and validation procedures in An et al. (2005, 2014). The simple test results show that the simulated profiles compare well with observed data (Fig. 10). Although this preliminary model uses limited data in a hypothetical landscape setting, it provides a basis for further development and testing.

When refined to include more detailed field data and process rules, as well as information regarding human decisions (i.e., conditions under which people would build fences) the usefulness of the ABM

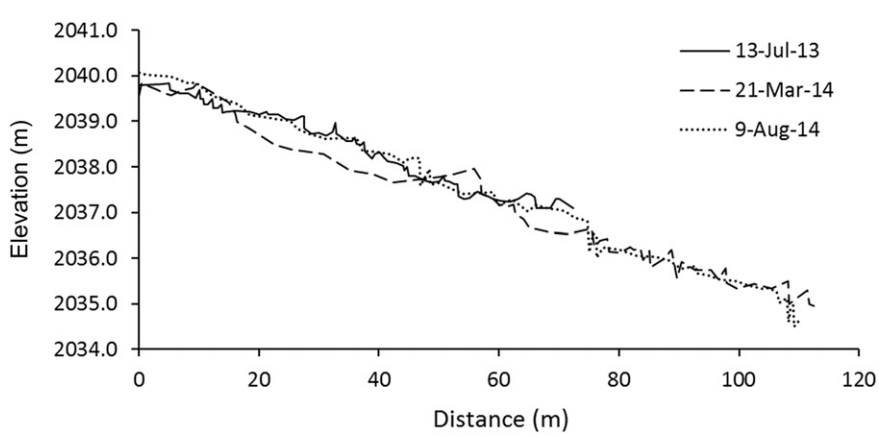

Fig. 8. Longitudinal profile of channelized reach downstream of lower fence, 9 August 2014.

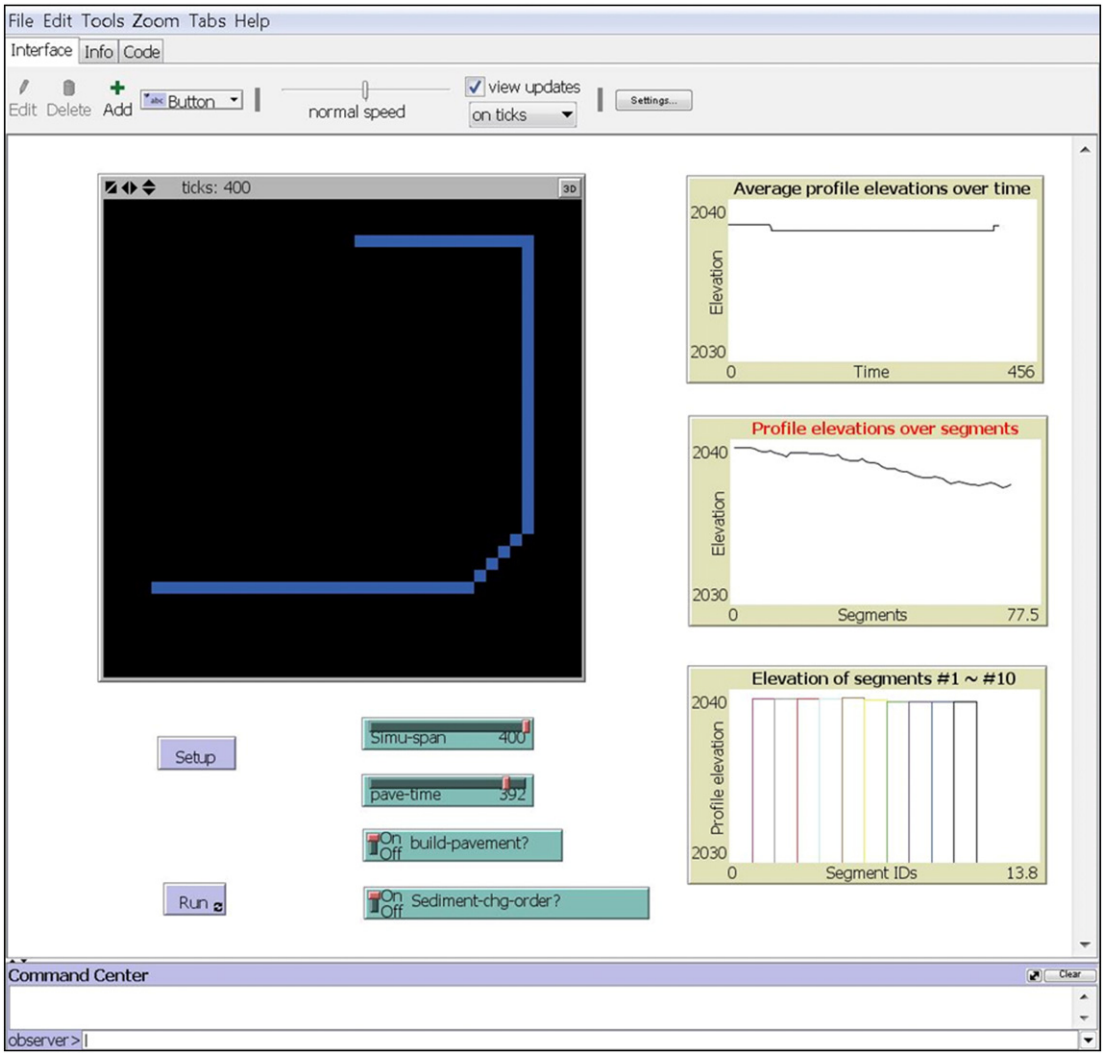

Fig. 9. The interface of the agent-based model developed in NetLogo. The window on the left represents the study channel against a black background depicting the neighboring hypothetical landscape (40 cells by 40 cells). The initial time (time zero) for this simulation is 13 July 2013. The graphs on the right show the average elevation of all 70 segments over time, the surface (profile) elevation of the segments at discrete time points (in this example, for day), and an illustrative elevation of the profile for the first 10 segments below the fence.

would be diverse. First, the ABM could provide a platform for scenario analysis and policy evaluation. For instance, by setting the building of the pavement at different times in relation to the timing of fence construction (i.e., the initial time for simulation, a user-defined parameter), the ABM could evaluate how the channel morphology (elevation) may respond in relation to seasonal variations. Second, because the ABM is both spatially explicit and temporally mobile (it predicts the channel elevation at any time points of interest), it could help to evaluate the timing of natural disasters or human intervention on landscape change. Third, the ABM could test more fully the feedback effects hypothesized on Figs. 1 and 3, when multiple feedback loops are included in the ABM. If further changes occur and people decide to build another fence at some distance downstream or elsewhere in the watershed, for example, the ABM could estimate how the new fence may induce additional

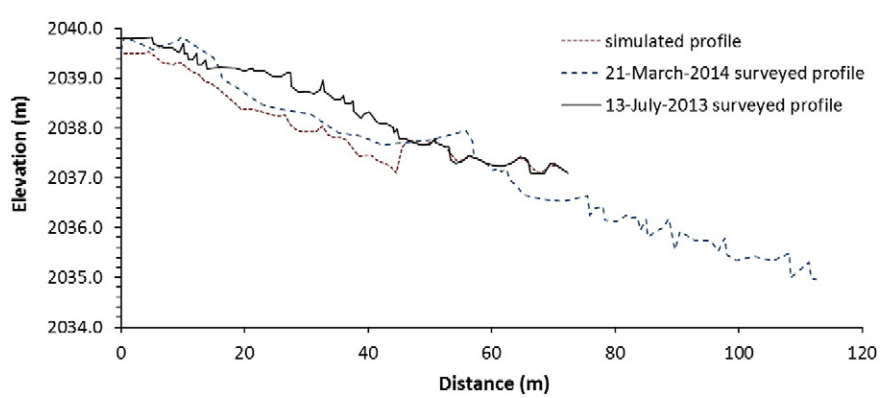

Fig. 10. Simulated profile resulting from ABM compared with topographical surveys.

change in river morphology besides those caused by construction of the first fence — changes to which people may respond further. In the future, if sufficient data could be collected to model people's decision-making when facing landscape change, including economic, social, or political factors, along with spatially explicit landscape data (e.g., forest and fuel location, fire/storm frequency), the simple and illustrative ABM outlined above could be extended further. The expanded ABM would be able to simulate various feedback loops between natural hazards (fires, storms, floods), human responses (fence building, channel paving), and landscape/channel alteration.

5. Discussion and conclusion

In summary, the interactions that occurred between human decisions and fluvial responses following the 2012 Waldo Canyon Fire of Colorado provided a timely case to capture feedbacks in the human–landscape system. These feedbacks occurred because of the construction of tall fences at the base of a burned watershed in response to perceived risks from post-fire geomorphological hazards. Instead of dampening the risks and hazards of fire as originally intended, these actions caused channel erosion and degradation, leading to further decisions and landscape change in a positive feedback cycle.

The feedback cycle documented here has, in fact, occurred similarly in other contexts. In urban areas, for example, eroding streams from increases in storm water runoff that may enlarge channels often prompt management responses to stabilize banks by channelization (Downs and Gregory, 2004). Stream erosion, however, may be a necessary process of adjustment toward larger channel capacities needed to accommodate changed hydrologic regimes in urban areas (Henshaw and Booth, 2000; Chin, 2006). These actions may therefore produce other deleterious consequences and further human responses, such as efforts within communities impacted by the negative effects of channelization to naturalize streams (Rhoads et al., 1999). Positive feedback cycles often characterize coupled human–landscape systems (Chin et al., 2014). Recognizing them is therefore a first step toward slowing or reversing environmental degradation, especially where coupling is indirect, diffuse, or weak, and where they involve threshold dynamics.

The example case described in this paper also provides a timely illustration of how feedback interactions between human and geomorphic systems could be investigated, both conceptually and methodologically. In the "Anthropocene" where human interactions with Earth systems are increasingly intense, a more complete research framework must encompass not only the human impact on Earth surface processes, but also the human responses interacting with physical processes. Although qualitative examples of such human–landscape interactions could be cited, challenges remain to identify and quantify the causal linkages across diverse systems. Thus, predicting the dynamics of many diffuse and potentially weak feedbacks remains difficult, especially because they occur over varying temporal and spatial scales.

Because of these challenges, integrative modeling tools become essential for quantifying and predicting the evolution of Earth's surface in response to human interactions. This study also demonstrates how one integrative tool, the agent-based model, provides a framework to simulate geomorphological change. Although ABMs are already common in studies of social–ecological systems (e.g., Brown et al., 2007; An et al., 2014), geomorphologists have only begun to explore their use. Challenges remain to gather sufficient data for both the physical and human systems – especially in quantifying human decision-making and behavior – to fully inform application of these models to adequately capture the dynamics of human–landscape systems. In this regard, collaboration between geoscientists and social scientists remains a high priority for meeting the grand challenges outlined recently for the research communities (NRC, 2010, 2012), in light of intensifying human interactions with Earth systems.

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