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Biodiversity resilience in the Central Indian Highlands is contingent on maintaining and recovering landscape connectivity: the tiger as a case study

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Abstract Corridors (variably called landscape linkages, connectors, and gateways) are expanses of a landscape that facilitate the flow or movement of individuals, genes, and ecological processes. Protected areas with their buffer zones and the corridors that connect them are cornerstones of modern conservation actions to maintain the biodiversity we have and restore what we have lost. Policy and governance to guide the establishment and management of protected areas and supporting buffer zones is well established in the Central Indian Highlands. A policy and governance structure to create the context and enabling conditions for corridor maintenance, creation, and recovery is emerging but is constrained by the reigning land-management paradigm that separates conservation from development rather than mainstreaming species and habitat conservation into the rural development agenda. Well-nourished, healthy human populations and healthy ecosystems are inextricably linked. The worsening ecological conditions in the Central Indian Highlands can trigger the emergence of a common agenda for an inclusive, caring, and environment-friendly mode of development. The alternative is the business-as-usual scenario: a continuation of worsening ecological conditions. Entry points through the biodiversity, agriculture production, resource extraction, and economic/social sectors to enable integrated sustainable landscape management are identified. These include deepening what it means to successfully conserve a species combined with explicit threat analysis for at-risk tigers and the landscapes that supports them; landscape scenario modeling to advance communication by synthesizing diverse forms of research and articulating and evaluating alternative socio-economic futures; and the use of the smart green infrastructure process as an approach to development rather than only as a way to mitigate environmental damage. Models are presented to scale up from isolated conservation interventions to collective impact that unites supportive government partners with individuals, NGOs, and economic interests to achieve viable long-term relationships in human and natural systems to value, maintain, and recover landscape connectivity.

Keywords Central Indian Highlands · Biodiversity · Connectivity · Corridors · Landscape · Conservation · Tiger · *Panthera tigris* · Resilience · Persistence

Introduction

The grandeur of the forests and wildlife of the Central Indian Highlands was described in Indian hunting books (Forsyth 1919; Dunbar Brander 1923). More recently, as the natural area has been diminished, conservation scientists have documented the remaining charismatic wildlife populations (Schaller 1967; Jhala et al. 2011), and environmental historians have traced the ecological changes resulting from human population growth and wildlife habitat destruction (Panwar 1987; Rangarajan 1996). Historically, and today, conservation policies and practice are outpaced by development (Thapar 2003). Maintaining biodiversity resilience in the face of ever-increasing anthropogenic disturbance is the conservation challenge for the next decades.

Here, I outline some of the ways our rapidly advancing knowledge and technologies can inform policy and management to achieve positive conservation outcomes in the Pench–Kanha Corridor, Satpura–Maikal Landscape, Central

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Indian Highlands, and more broadly, the Central India landscape complex (CILC; Fig. 1). We need enhanced frameworks, platforms, and processes to achieve positive landscape-scale conservation outcomes, including maintaining biodiversity resilience. There is no tried and true recipe for scaling up from site-based to landscape-based outcomes. We progress by doing, measuring, adapting, and doing again.

I focus on the imperiled wild tiger (*Panthera tigris*) with the understanding that saving wild tigers means managing their supporting landscapes at a scale that allows long-term tiger population persistence. The wild tiger in India is the face of biodiversity conservation. Learning to manage sustainable landscapes is a crucial societal challenge requiring innovative solutions. After clarifying the landscapes of interest and some terms and concepts, I provide the ecological context of worsening ecological conditions in the highlands, observations on what it means to successfully conserve a species such as the tiger and its supporting landscape, describe a vision for a better future, examine some new tools to create entry points to processes for sustainable landscape management, present some collective-impact platforms that can serve as models for increasing biodiversity resilience in the CILC, and provide ideas on the critical role played by conservation leadership in implementing and sustaining this process.

Ecological resilience, persistence, and tiger conservation landscapes

Tiger conservation landscapes in Central India

The concepts of tiger metapopulation dynamics, connectivity in tiger conservation landscapes (TCLs), and long-

Fig. 1 The Central Indian landscape complex and its relative location in India shown in the *inset*. Satpura–Maikal landscape is bounded by *purple*. State boundaries are shown in *black*. Forest cover data in *green* are from Hansen et al. (2013). Protected area boundaries are in *red*. *K* Kanha, *P* Pench, *S* Satpura, *M* Melghat tiger reserves are marked (color figure online)
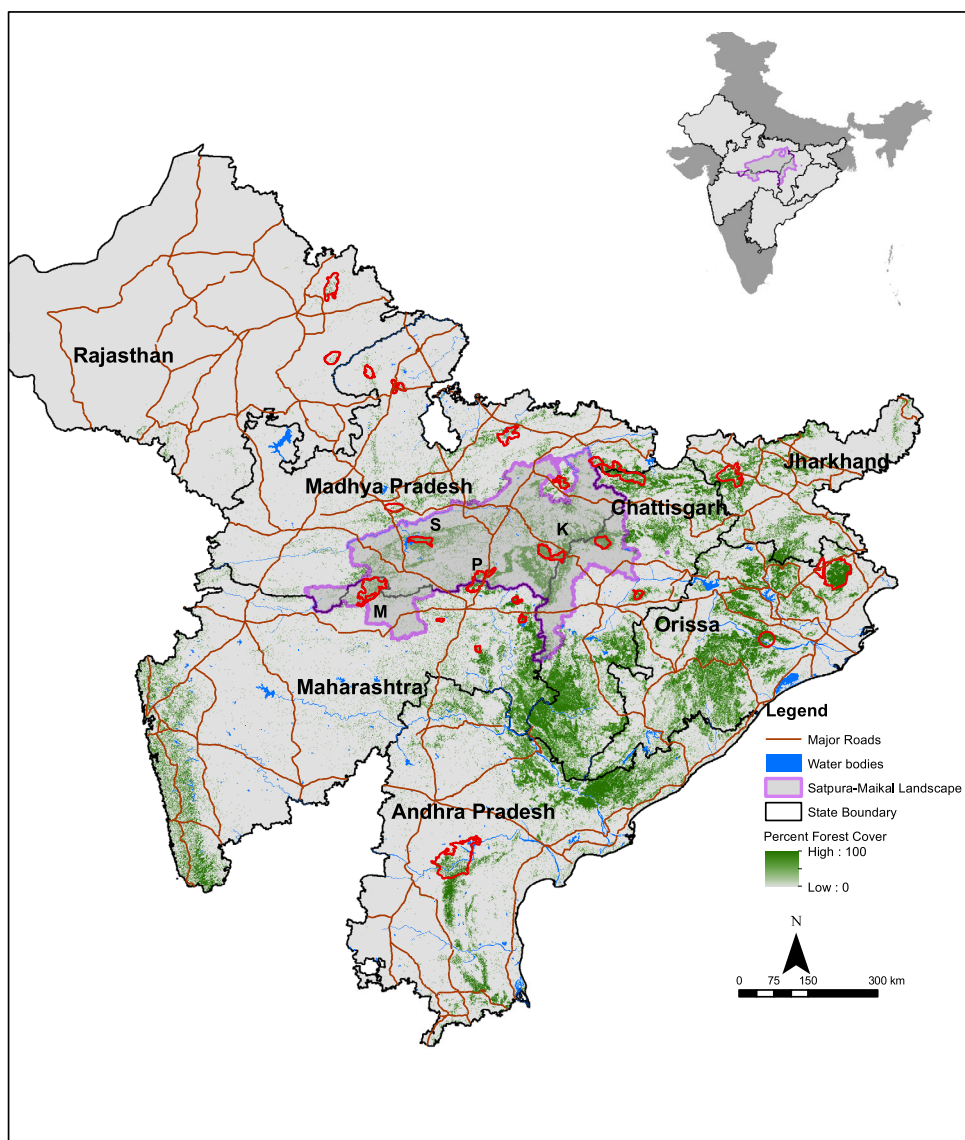
term tiger population persistence will be central to evolving conservation policies that sustain biodiversity resilience. A metapopulation is "a group of partially isolated populations of the same species that undergo local extinctions and recolonization" (Frankham et al. 2010:533). Thus, the dynamics of metapopulations depends on the effective dispersal of individuals or groups between habitat patches in the landscape mosaic.

Different scientific teams have use varying approaches to defining TCLs. For the purpose of reporting on the status of tigers and prey, India's National Tiger Conservation Authority groups the tiger-occupied forests in India into six landscape complexes (Jhala et al. 2011). The CILC is bounded by the Aravlli Range, Satpura Range, Chota Nagpur Plateau, and the Odisha Hills in eight states and is drained by some of India's principal rivers including the Chambal, Damodar, Godavri, Mahanadi, Narmada, Son, and Tapti. There are 22 tiger reserves and more than 40 other protected areas in this landscape complex where tiger were known to occur in 2010 (Jhala et al. 2011). The CILC encompasses six different ecoregions in the tropical and subtropical dry broadleaf forest biome, with areas in the tropical and subtropical moist forest biome. An ecoregion is "… a relatively large area of land or water that contains a geographically distinct set of natural communities that share a majority of their species, ecological dynamics, and environmental conditions, and function together as a conservation unit at global and regional scales" (Wikramanayake et al. 2002:17).

Within this vast area, about 600 tigers occupied 38,056 km^2 out of a total of 338,375 km^2, or 11 %, in 2010; tigers were distributed among 23 populations and were grouped into seven hypothesized tiger metapopulations, with three classified as fully functional ones that "…have a long-term future provided they remain connected through corridors" (Jhala et al. 2011:xi), and four in landscapes that have the potential to harbor tiger metapopulations if fragile and or stepping stone connectivity is maintained, or better, is functionally restored (Jhala et al. 2011:55). The methods of grouping these population into metapopulations was through least-cost and least-resistance corridor pathways aligned on high-resolution satellite images and not through spatial genetic analysis or the analysis of tiger gene flow.

Sixteen tiger metapopulations were hypothesized to occur in the same landscape space in an earlier taxonomy of TCLs (Sanderson et al. 2010) where a TCL "…is a block or cluster of blocks of potential effective habitat within 4 km of each other, meeting a minimum, habitat-specific size threshold, where tigers have been confirmed to occur during the last 10 years and are not known to have been extirpated since the last observation." Each TCL was postulated to be a distinct tiger metapopulation and not connected through dispersal events and gene flow with other TCLs (Sanderson et al. 2010:149). These criteria for grouping forest blocks in TCLs were based on an earlier radio-telemetry study of tiger dispersal behavior and distances moved (Smith 1993).

The 160 km, 2200 km^2 Kanha–Pench corridor connecting the Kanha and Pench tiger reserves is the approximate geographic center of the CILC (Jena et al. 2011; Rathore et al. 2012). The Central Indian Highlands, which includes the Kanha–Pench corridor, was classified as a distinct biogeographic province within the Deccan Peninsula (Rogers and Panwar 1988), and encompasses the Satpura and Vindhya ranges, parallel east–west chains of hills. The 45,000 km^2 Satpura–Maikal Landscape, which encompasses the Kanha, Pench, Melghat, and Satpura tiger reserves and connecting corridors within the Central Indian Highlands, forms the upper catchment of the Narmada and Tapti rivers and was the study site for the tiger landscape genetic assessment made by Sharma et al. (2013a, b) discussed below.

In efforts to define tiger metapopulations, the challenge is in quantifying connectivity and the degree of movement tigers have in a landscape mosaic. The process of quantifying connectivity for analysis, and then for practical application to create conditions that permit connectivity maintenance and recovery at the landscape scale is the central challenge for designing conservation actions that will result long-term tiger population persistence (Jhala et al. 2011; Wikramanayake et al. 2011; Qureshi et al. 2014). There are two components to connectivity: the structural arrangements of different habitats in the landscape and the behavioral or functional response, and movements of individual tigers in response to the physical structure of the landscape (Crooks and Sanjayan 2006). "Corridors (variably called landscape linkages, connectors, gateways, etc.) are the most popular means to achieve connectivity" (Noss and Daly 2006:588). Functional connectivity has been measured by tracking individual animals through camera-trap grids (Singh et al. 2013); with radio-telemetry (Smith 1993) as radio-collared tigers move through the landscape mosaic; through estimating tiger habitat occupancy over broad forest tracts (Jhala et al. 2011) or a more focused effort in a target forested corridor (Jena et al. 2011); and by measuring effective dispersal (migrants) and gene flow, which has only recently been done in this landscape and is summarized below. The challenge with all four approaches is to accurately measure and align the landscape or habitat structure with the tiger's functional response to that structure.

Tiger-prey dynamics, reproducing female territory size, and tiger density

The space required by individual breeding tigers is set by prey abundance. In the absence of human-induced

mortality, prey density and distribution, rather than habitat vegetation parameters, explain tiger density (Karanth et al. 2004; Miquelle et al. 2010). Tiger prey densities vary across different forest types because the production of the available food for ungulates varies in different forest types (Eisenberg and Seidensticker 1976). Measured tiger densities vary from 0.5 (tigers older than 1 year)/100 km^2 in the temperate forest of the Russian Far East and Southeast Asian tropical rain forests to more than 20/100 km^2 in the prey-rich floodplain savannahs and riverine forest of Nepal and India (summarized in Seidensticker 2010). Tiger densities in CILC vary from 1 to 16 tigers (over 1 year old)/ 100 km^2, and within the principal tiger reserves considered here, Kanha had 6 tigers/100 km^2, Pench 4 tigers/100 km^2, and Satpura and Melghat each about 2 tigers/100 km^2 in 2010 (Yumnam et al. 2014).

The largest obligate meat-eaters living in Asian wildlands, tigers kill prey ranging in mass from 20 kg to more than 1000 kg as encountered, but selectively seek and kill large-bodied ungulate prey—large deer (*Cervus* spp., *Axis* spp. *Rucervus* spp., *Rusa* sp.), wild cattle (*Bos* spp., *Bubalus* sp.), and wild pigs (*Sus* sp.)—thereby gaining access to a major percentage of potential prey biomass that is contributed by relatively few individuals (Seidensticker et al. 2010; Hayward and Jedrzejewski 2012). Adult tigers need to kill one large prey animal about once a week (Karanth et al. 2004), but the energy needs of a tigress raising cubs over the reproduction period more than double this requirement (Miller et al. 2014). Tigers are estimated to remove about 10 % of the standing crop of prey biomass annually (Sunquist 1981).

The acquisition of an exclusive territory is necessary for successful breeding in both sexes of tiger, and for females to rear cubs. The home range of a reproducing female is defended against other reproducing females and is overlapped by a breeding male's territory; a territorial male can overlap 1–7 breeding female territories (summarized in Seidensticker 2010). The territory size of reproducing females is the base measure of carrying capacity for tigers. When the population density of breeding females is less than that set by prey availability, because of poaching or other mortality, females expand their territory size to include more prey than are energetically essential. As female numbers increase, a young adult female tiger displaces her mother from her territory, takes part of the mother's territory, displaces an adjacent female from her territory, or displaces a female further afield. This phylopatric land-tenure dynamic results in clusters of related females living in adjacent territories (Goodrich et al. 2010; D. Smith and C. McDougal personal communication, December 2014). Territory size of eight breeding females radio-tracked in two Indian protected areas in seasonal dry tropical forest ranged from 17 to 27 km^2 (Simcharoen et al.

2014). With this measured variation in tiger density in the same biome, presumably supporting about equal prey biomasses, we have an estimated range of what breeding female tiger carrying capacity could be in the CILC protected areas, but we have yet to partition the impact of any minimum area social tolerance among breeding females, and of poaching, other human disturbances, and prey abundance and distribution that shape breeding tiger densities in the CILC protected areas.

Adult female tiger survival and tiger population persistence

Tiger-prey dynamics is the energy availability-exchange dimension of the conservation picture, and the most apparent. But the conditions that enable a population's persistence over time, with its genetic, demographic, and spatial components, are the covert dynamic, much less amenable to quantification, and therefore, the most contentious when seeking political support for sustainable long-term tiger population persistence. We do know that small tiger populations, <30, are fragile, unstable, and vulnerable to extinction, and will crash with only a 2 % kill rate, so even a modest amount of poaching will induce extinction. Larger populations, ∼80, can withstand a 10 % kill rate (Darmania et al. 2008).

Adult female survival is a key factor in tiger population persistence. Further work on this stochastic demographic dimension of tiger population persistence demonstrated that a viable population with adult breeding female survival of 0.85 would require 83 breeding females to be sustainable and even at this size the population will decline when more than 15 % of the breeding adult females die each year (Chapron et al. 2008). Adult males are not a limiting factor in large felid populations, as long as there are some, but when the territorial structure of the adult males is disrupted by poaching events, incoming males replacing poached resident males kill cubs to increase mating opportunities (known as sexually selected infanticide) (Kenney et al. 1995), which is additive in reducing cub production, population growth, and population persistence.

A challenging dimension of tiger population persistence has been estimating the impact of inbreeding depression and genetic drift and measuring gene flow in tiger populations living in large landscapes with fragmented habitat mosaics. Understandably, this has been the most difficult dimension to convey to policy makers and those managing infrastructure development for resource extraction. Thirty years of scientific work and modeling "…collectively shows that thousands (not hundreds) of individuals are required for a population to have acceptable probability of riding-out environmental fluctuations and catastrophic events, and ensuing the continuation of evolutionary

processes" (Traill et al. 2010:28). While true, that high number is off-putting and a nonstarter in conservation policy discussions regarding alpha predators and many other at-risk species. All the tiger populations in the CILC were each estimated to total 75 individuals or fewer (Jhala et al. 2011).

The diploid lethal equivalents, which are detrimental alleles that would cause death if homozygous, are unknown in wild tiger populations. By using published levels of lethal equivalents in mammals, because there is no evidence that tigers are not as susceptible to inbreeding depression as other mammals, Kenney et al. (2014) simulated inbreeding depression in small (12 breeding females), medium (24 breeding females), and large populations (48 breeding females). For the smallest population, even four dispersing tigers coming into the population per generation (7 years) did not increase population viability and yielded a likelihood of extinction of more than 90 % within 30 years. Medium-sized populations will reach a serious threat of extinction within 75 years. Medium- and small-sized tiger populations are the norm in the CILC tiger reserves. No tiger reserve populations in the CILC are large enough to have 48 breeding females, the largest population considered by Kenney et al. (2014). The risk of inbreeding depression decreases the more breeding females there are in the population. Thus, both the demographic and genetic dimensions of long-term tiger population persistence require a land management program that connects populations to allow greater gene flow between subpopulations to mitigate further inbreeding depression and increase tiger populations resilience (Jhala et al. 2011; Wikramanayake et al. 2011; Kenney et al. 2014).

Gene flow in Central Indian tigers

Neither the TCL taxonomies hypothesized by Sanderson et al. (2010) nor the tiger metapopulations postulated by the National Tiger Conservation Authority (Jhala et al. 2011) in the CILC were based on an actual analysis of tiger genetic structure and gene flow in the landscape complex. It has only recently become possible to study genetic structure and gene flow through noninvasive means by extracting genomic DNA from fecal samples systematically collected throughout the landscape complex. Three such studies that do this are now available (Sharma et al. 2013a, b; Joshi et al. 2013; Yumnam et al. 2014) in the CILC. Although the studies are not directly comparable because of differences in the regions in the landscape covered and different microsatellite markers employed, the results provide direction for policy makers and practitioners seeking to maintain and recover landscape connectivity and thereby increase biodiversity resilience in the Central Indian Highlands and in the larger CILC.

A long-term study of tiger dispersal behavior in the Nepal Terai revealed how dispersing radio-collared tigers shunned agricultural open areas and areas of high human activities (Smith 1993). The authors of these recent genetic studies were surprised by the extent to which tigers exchange genetic material through functional corridors. "The tiger population in central India still exists as a metapopulation with gene flow occurring between most populations clusters in contemporary times" (Yumnam et al. 2014:23). Tigers were dispersing through more suboptimal habitat than experts believed probable. There also were no bottlenecks detected in the central and southern protected areas in the CILC although there appear to be bottlenecks with little or no gene flow among northwestern and northern protected areas and those in the center and south. The most functional corridor for the exchange of genetic material was between the Kanha and Pench tiger reserves which are connected through a forested corridor (Sharma et al. 2013a, b, Yumnam et al. 2014). However, there has been a 47–70 % reduction in effective dispersal events (first- and second-generation migrants) between the Kanha–Pench source populations and the other tiger reserves such as Kanha–Melghat, Kanha–Satpura, and Pench–Melghat which are connected by agricultural areas and degraded forest corridors. Aside from the Kanha–Pench connection, other tiger reserves still connected through forest corridors—Satpura–Melghat, Satpura–Pench—showed no significant change in gene flow (Sharma et al. 2013b).

How genetically connected are tigers in other regions of the CILC to tigers living in the Central Indian Highlands? I noted above the genetic disconnect between the north and northwest tiger reserves and those centrally located. Positioned at the southern edge of the CILC, the Nagarjunasagar–Srisailam tiger reserves have been off limits to scientists until very recently because of insurgent activities, but apparently not off limits to effective tiger dispersal events with one tiger moving over 600 km to Kanha and Pench (Joshi et al. 2013). Tigers and their genes are not constrained by the boundaries of protected areas in the CILC, but the tigers living here have a fragile existence because of low numbers and tenuous, at-risk connections between populations; long-term tiger population persistence requires the maintenance and enhancement of connectivity so they are managed as a metapopulation.

Ecological conditions in the Central Indian highlands are worsening

The iconic wildlife living in these highlands is under intensifying stress from many factors within and around the region's protected areas. This stress stems largely from

India's need for energy and other natural resources to support its expanding economy and feed a growing human population (Mukerjee 2014). How these pressures on lands and resources are managed will determine the fate of the tiger and its supporting highland landscape, which is a global and national treasure.

Descriptions in English of the people, forests, and wildlife of the highlands are relatively recent, dating from James Forsyth's 1862–1864 tour (Forsyth 1919). Carefully read, Forsyth documents a remarkable landscape transformation then befalling one of India's wildest frontiers. Sharma et al. (2013a, b) found the historical echoes of habitat fragmentation in this landscape imbedded in the current tiger population's genes. Tigers entered this landscape ten millennia ago; population subdivision began about one millennia ago; and began accelerating 200 years ago. Over the last 300 years, the highlands lost 78 % of forest cover to agriculture and urbanization. In the past few decades, the rate at which the human footprint expanded is unparalleled (Sharma et al. 2013b). Yet, this is a global priority TCL (Dinerstein et al. 2007).

More than 40 % of India's wild tigers live in the CILC and the population numbers have been stable since 2006, though habitat occupancy decreased by 20 % between 2006 and 2010 (Jhala et al. 2011). Using a high-resolution monthly forest clearing database from 2000 to 2005 in the Indian TCLs described above (Sanderson et al. 2010), Dasgupta et al. (2014) found a trend change rate for forest clearing of −0.25 %/month. They noted, however, that formal protections in Indian TCLs significantly reduced forest clearing. Anup Joshi (personal communication, May 15, 2015) found a nearly 500 km^2 loss of forest cover between 2001 and 2013 from the 16 TCLs in the CILC using the World Resources Institute Global Forest Watch tool (Hansen et al. 2013).

The intense struggle to free tigers and other wildlife from the extinction vortex in the highlands began by banning organized sport hunting and establishing protected areas in the early 1970s with Project Tiger (Task Force, Indian Board for Wild Life 1972; Panwar 1987). The economic model that the frontier is unending and to be exploited extends deep into human history (Richards 2003). But now, in this last vestige of wild India, economic wants are crashing against the reality of a closed frontier, exposing the myth of the unending frontier on which the current and planned economic and resource extraction model is based. A misinformed enforcement of the unending frontier resource extraction model will upend the habitat connectivity linkage network on which the long-term persistence of large mammals in the highlands depends and will become an important biodiversity policy failure.

A vision for the sustainable future of the Central Indian Highlands

The sustainable future of the Central Indian Highlands is grounded in thinking big to mainstream species and habitat conservation into the rural development agenda. Think of the highlands of Central India as what they are and can be as a biodiversity haven with verdant forests and meadows, and providing wood and other forest products for healthy people, clean and abundant water, subcontinent–scale habitat corridors, and a globally important source of renewable energy and carbon storage. Well-nourished, healthy human populations and healthy ecosystems are inextricably linked (Laurance et al. 2014).

The ecological resilience of the Central Indian Highlands appears to be stretched very thin, feasibly near a tipping point. Ecological resilience is the capacity of an ecosystem to tolerate disturbance without switching to a qualitative different state that is controlled by a different set of processes; engineering resilience is the time taken to return to a pre-disturbance state (Standish et al. 2014). A policy and governance structure to create the context and enabling conditions for corridor maintenance, creation, and recovery is emerging (Table 1) but is constrained by the reigning land-management paradigm that separates conservation from development rather than mainstreaming species and habitat conservation into the rural development agenda. The worsening ecological conditions in the Central Indian Highlands can trigger the emergence of a common agenda for an inclusive, caring, and environment-friendly mode of development. The alternative is the status quo: a continuation of worsening conditions in connectivity linkages and biodiversity resilience.

Seeking entry points for integrated landscape management to mainstream species and habitat conservation into the rural development agenda

A way forward to bring conservation into the rural development agenda is the development of an integrated multidisciplinary perspective. Best practices in sustainable landscape-scale management are emerging in India, but vested economic, especially resource extraction, models resist their implementation. Among the ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses is finding a common point of entry in the conversation (Sayer et al. 2013).

What is required to successfully conserve the tiger?

A traditional entry point for enabling conservation collaboration between scientists and management at both the site and landscape level is an explicit threat analysis for the at-

Table 1 Policy tools available to support improving biodiversity resilience by maintaining and recovering landscape connectivity in the Central Indian Highlands

Legal platforms	Purposes
Indian Forest Act, 1927	Protects forests from illegal activities, including unauthorized felling and fires
Forest (Conservation) Act, 1986	Protects forest from unauthorized diversion of forest land for non-forest purposes
Environmental (Protection) Act, 1986	Demark ecological sensitive zones; take all measures necessary for protecting and improving the environment and to prevent and control environmental pollution
National Forest Policy Act, 1988	Targets actions to bringing 33 % of India's landmass under forest and tree cover
Wildlife (Protection Act), 1973, as amended in 2006	Established the legal authority to declare Tiger Reserves with dedicated core areas and buffer zones
	Established legality of the concept of critical tiger habitat
	Provided for establishing the preparation and implementation of tiger conservation plans to ensure ecologically compatible land-uses to address concerns of livelihoods of local people and provide dispersal habitats and corridors
	Ensure tiger reserves and areas linking one protected area or tiger reserve with another tiger reserve are not diverted for ecologically unsustainable uses
	Establish community reserves to be jointly managed with local stakeholders and communities

risk-species and the landscapes that support them. The best indicator of a landscape's health can be read in the status of the alpha carnivores that live there. "There is now a substantial body of research demonstrating that, alongside climate change, eliminating large carnivores is one of most significant anthropogenic impacts on nature" (Ripple et al. 2014:1241). The crucial societal challenge is devising creative new ways to maintain viable populations of large mammals in the face of threats posed by alternative land uses.

Safeguarding wildlife and forests is a process that will have to continue to invent itself to flourish. There is a tendency to view threats as static but the suite of threats emerges and changes as economic and ecological contexts change. Stopping organized sport hunting and commercial traffic in tiger skins was paramount when Project Tiger was launched (Task Force, Indian Board for Wild Life 1972). The destruction, modification, or curtailment of tiger habitat and range and loss of connectivity was not seen as critical as it is today. Disease was not then seen as critical, but it is an emerging threat (Gilbert et al. 2014). As the relentless killing of tigers has continued, there is a growing consensus that existing safeguards for wildlife are insufficient. The law on the ground is in many places very different from the law on the statute books. Policy and enforcement tools to enhance protective efficiency are vital (Darmania et al. 2008). We have a deeper understanding of what can and especially cannot be expected of small protected areas alone in supporting long-term population resilience, as discussed above. The essential need to maintain metapopulations to increase resilience of conservation-dependent species was known from theory (Wikramanayake et al. 2011), but only in the last decade have we had the tools to measure a species' gene flow and barriers to gene flow across large landscapes as outlined above (Sharma et al. 2013a, b).

Conservation biologists are deepening what it means to successfully conserve a species and the three "Rs"—representation, resilience, and redundancy—are paramount (Redford et al. 2011). A successfully conserved species will be self-sustaining demographically and ecologically; be genetically robust; have healthy populations; have representative populations distributed across the historical range; have replicate populations within each ecological setting; and be resilient across the range. Protected areas are the cornerstone of efforts to conserve biodiversity. But my colleagues and I found that with present trends and the business-as-usual scenario, we can expect a 43 % loss of the most suitable tiger areas range-wide by 2020 through agriculture expansion and urbanization (Wikramanayake et al. 2010). We did not include habitat loss to mining and supporting infrastructure in our study, but if included, this would significantly add to the loss of tiger habitat. The business-as-usual scenario is not even a viable holding action. The tiger's future is tied to effective protection, enhanced habitat connectivity, and habitat restoration. Corridor identification mapped in the *Status of Tigers Co-predators and Prey in India, 2010* (Jhala et al. 2011) and further elucidated by Qureshi et al. (2014), Yumnam et al. (2014), and Dutta et al. (2015b) is a conservation milestone and entry point into the landscape management paradigm essential for long-term persistence of the tiger and other at-risk wildlife in the CILC.

Landscape scenarios to advance the conservation dialogue

An emerging tool to create new entry points are landscape scenarios to advance our communications. For example, Harvard Forest scientists have advocated a vision for the New England Landscape of the USA. Their *Wildlands and*

Woodlands vision (Foster et al. 2010) calls for retaining 70 % of the region in forest lands; striking a balance between active forest management and preservation; addressing the growing instability of the forest base that supports human livelihoods and regional biodiversity; and leaving room for doubling the amount of developed lands. This is a shared vision for New England's future among private landowners, communities, regional organizations, and state and national collaborators. The model they are creating informs how we can meet our challenges in the Central Indian Highlands.

With this vision in hand, the Harvard Forest scientists moved on to a series of scenario studies, which is a powerful approach to synthesizing diverse forms of research, articulating and evaluating alternative socioecological futures, and encouraging perceptive thinking in this era of unprecedented global change (Thompson et al. 2012). The details are not necessary here, but the shift to process-oriented activities is. The communication entry point is achieved through multiple collaborative scenarios that respond to different views of the future proposed by non-scientists, usually community and government leaders. These scenarios do not attempt to predict the future, but they enable us to see and evaluate some of the many consequences of different approaches to using and caring for the land. They present contrasting views of the future that are simulated using cutting-edge models. Scenario studies are especially valuable as socioecological change approaches "tipping points", as I believe we are approaching for some critical ecological process in the highlands, where the need to anticipate and mitigate future change is acute.

Smart green (wildlife friendly) infrastructure

The smart green infrastructure (SGI) process is also an entry point, but not an alternative, in the sustainable landscape conversation. In Central India, coal mining and thermal power plants, widening of highways, gauge conversion of railroad lines, and teak monoculture are major contributors to habitat fragmentation leading to biodiversity loss and creating precarious conditions for tigers and sloth bears (*Melursus ursinus*; Dutta et al. 2015a). Dutta et al. (2015b) mapped nearly 50 "pinch points" where rail lines and highways bisect connectivity linkages in the 35 habitat linkages among 16 primary protected areas. It is always tragic when a tiger is killed by poachers. I was particularly saddened when I read the paper on the fate of a dispersing tiger from the Ranthambhore Tiger Reserve. After dispersing an airline distance of 147.3 km through what to a tiger is a barren and hostile landscape, an adult male was hit by a train and killed on the tracks bisecting

the Mukandra Hills-Dara National Park (Singh et al. 2013). Tigers lost some good dispersal genes there.

Knowing the challenges to maintaining habitat connectivity posed by infrastructure, the SGI concept was introduced by the Global Tiger Initiative Secretariat at the Kathmandu Global Tiger Workshop in 2009. SGI is infrastructure that avoids tiger habitats, minimizes and mitigates adverse impacts through tiger-friendly design, and compensates for any remaining damage to have a net positive impact. SGI is based on best practices globally (Quintero et al. 2010). SGI emphasizes the importance of regional strategic environmental assessments as well as environmental assessments. SGI emphasizes avoidance policies and land-use planning in priority TCLs. The concept of "no-go" areas based on global priority, presence of tiger populations, growing threats, high biodiversity value, and genetic variation are identified where stringent infrastructure policies need to be applied.

Engineering and building the actual tiger-friendly infrastructure is the final stage in the SGI process. Long before reaching this stage, vertical and horizontal integration in the strategic environmental planning process has to be rooted in legislation as an approach to sustainable development rather than only to mitigate damage, or even, as an end in itself. Deciding where to site an infrastructure project is based on a comprehensive planning flow chart that includes specific planning steps and mitigation hierarchy requirements. If governments apply tiger-friendly policies but cannot mitigate impacts adequately, they should stop the project in priority landscapes and perform alternative analysis. An example of applying SGI principles is the corridor-connecting the Main Spine and the Taman Negara landscapes in Peninsular Malaysia (Quintero et al. 2010).

Scaling-up of best practices for sustaining large, ecologically sensitive landscapes

In the Indian Constitution, "…the State shall endeavor to protect and improve the environment and safeguard the forests and wild life of the country". This is a goal, not a given. Conservationists have relied on public sympathy toward broad conservation objectives to sustain India's wild nature, but with India's accelerated urbanization and economic growth, the future of the little that is left of India's wild nature remains principally in the hands of those who directly exploit natural resources for subsistence and commerce. Safeguarding vulnerable and fragile wildlife and landscapes demands a continual updating of India's conservation narrative by incorporating new knowledge and enlarging the narrative's context to include

emerging threats. One entry point into policies and actions to sustaining large, ecologically sensitive landscapes with a significant natural component is to look for best practices in sustaining other such landscapes and transfer knowledge and implementation processes through communications. Multiple approaches to landscape management with partnerships between state agencies and civil society are evolving as a best practice for sustainable landscape management in several countries, including India.

India's Western Ghats

In India, in the Western Ghats, after extensive consultation and review, the Western Ghats Ecology Expert Panel, convened by the Government of India's Ministry of Environment, Forests and Climate Change, in 2011, proposed that the entire Western Ghats be designated an ecologically sensitive area and zoned based on threats and level of risks. The Expert Panel recommended that the Western Ghats be managed by a new entity: the Western Ghats Ecology Authority. The drama is being played out with the vested economic model having the upper hand, for now (Padma 2013). But this is a ground-breaking innovation and the long-term path proposed for a sustainable Western Ghats can serve as a model in the Central Indian Highlands.

The crucial elements in the Western Ghats example that can inform similar efforts in the highlands are (1) a shared agenda for the long-term welfare of the wildlife and people who live there; (2) partnerships that make management possible; (3) a management plan based on sustaining this ecologically sensitive landscape; (4) sufficient funding; and (5) legal enforcement. Integrating efforts among national and state ministries, and nongovernmental organization requires conservation leaders with significant training in building adaptive governance and management programs, fostering cooperation, and improving communications (Black et al. 2011; Bocetti et al. 2012).

The Western Ghats example is one of an emerging paradigm for integrated landscape management and investment in order to transcend business-as-usual. A recent review identified more than 250 financial institutions that are supporting multi-objective investment within landscape contexts (Shames et al. 2014). In Africa for example, 87 integrated landscape management initiatives are being implemented in 33 countries (Van Brouwershaven 2014).

Scaling-up from isolated interventions to collective impacts at landscape scales

The Global Tiger Recovery Program (GTRP) is a model for scaling-up from isolated interventions to collective impact (GTI 2011; Seidensticker 2010). The challenge of evolving frameworks to scale up from isolated interventions to larger scales is common to many endeavors where we seek to improve our quality of life and the lives of those species with which we share this planet (Kania and Kramer 2011). Our societal challenges to create enhanced frameworks, platforms, and processes to achieve positive landscape-scale conservation outcomes are of the same class and as diverse as those facing education reform and agriculture intensification, for example.

Saving and restoring tigers in this human-dominated world is conservation action that demands mutually reinforcing bottom-up and top-down cooperation. The Global Tiger Initiative Secretariat (GTI) escorted GTRP implementation by employing a collective-impact conservation paradigm that united high-level political support and supportive government partners with NGOs, individuals, and economic interests who understand and value the tiger's ecological and long-term survival requirements (GTI 2011). Collective impact overarches isolated interventions by individual organizations and isolated government departments, with the goal of long-term tiger population persistence and the sustainability of the tiger and the biodiverse landscapes that sustain tigers.

Conditions for collective success are a common agenda—Tx2 (double the number of wild tigers by 2022), shared measurement system, mutually reinforcing activities, continuous communications, a backbone support organization, and funding for collective best practice impacts. Collective-impact conservation builds on partnerships, in which trust is based on science-based verification. Science-based verification requires continuous communication among scientists, practitioners, constituents, and community leaders. Collective-impact conservation cannot be imposed from above; it is ultimately driven by local interests, skills, traditions, wants, and needs. New knowledge and innovative sensible solutions are conceived when diverse stakeholders with different interests, knowledge, and skills come together to share experience, learn from one another, and participate in decision-making processes. Collaboration and dialogue facilitate a deeper shared understanding of the challenges and reduce potential for conflict and redundancies. Collective-impact conservation is the platform to achieve viable, long-term relationships in human and natural systems. This global model can be effectively applied regionally to each of the major conservation landscapes in India identified by the National Tiger Conservation Authority.

Priority actions on which to build a collective-engagement platform

Building a collective-engagement conservation platform for the Kanha–Pench Corridor specifically, and the Central

Indian Highlands generally, begins with prioritization of activities. I suggest the following activities could focus a collective-engagement platform. However, after consultations, the prioritization of actions will need to be responsive to expressed needs from stakeholders because bottom-up self-organization is a critical element in a successful process. An entry point is to build on the groundbreaking work of Jena et al. (2011) and Rathore et al. (2012) to access existing opportunities to maintain landscape connectivity in the Kanha–Pench Corridor. Continue to refine the work of Qureshi et al. (2014) and Dutta et al. (2015b) for identifying dispersal corridors and "pinch points" that threaten connectivity in the entire CILC by conducting similar assessments of opportunities for connections among other protected areas. Continue to monitor all corridor use by tigers and their prey using habitat occupancy methodology and continue to monitor tiger, leopard, and sloth bear gene flow. Study the actual movement behavior of tigers in response to the habitat mosaic and structures in corridors. This is essential knowledge needed to construct a viable connectivity policy framework for strengthening biodiversity resilience in the Central Indian Highlands.

Employ the principles of the SGI to address blockages to wildlife movement into and through corridors. Dutta et al. (2015b) found that 35 linkages between 16 protected areas in the central Indian landscape were intersected by major roads in 35 places and by railroads in 43 locations. To be effective, the planning process has to move from a project-by-project-based approach to regional strategic assessment with the goal and value of maintaining habitat connectivity.

To move the biodiversity resilience agenda forward, academics can work with planners and community and government leaders to develop multiple collaborative scenarios that respond to different views of the future, particularly in maintaining biodiversity resilience and in basic sustainable resource conservation, such as future water supplies to the larger region, feasible and sustainable. Multiple collaborative scenarios will be an essential tool to enable government authorities to define and refine governance authority and incentives for wildlife corridors.

Trust is essential and can be facilitated by developing a coordinated response to immediately mitigate and resolve predator-livestock issues in the Central Indian Highlands protected areas, buffer zones, and corridors (Karanth et al. 2012). Just as important is to be proactive and identify risk zones (Miller 2014). It is neither fair nor sustainable for local farmers and herders to bear the brunt of the costs of wildlife-related losses. The Kanha and Pench tiger reserves, buffer zones, and corridor are an ideal zone to pilot the wildlife premium mechanism (Dinerstein et al. 2013) as a way to compensate for losses from wildlife and partner with local herders and farmers for a biodiverse and sustainable Central Indian Highlands.

Effective conservation leadership

Today we are standing on the shoulders of giants, of conservation leaders who have gone before. Elements of leadership and conservation effectiveness are being distilled in order to move beyond command-and-control to systems thinking (Black et al. 2011). Learning just how the ecological systems of the highlands of central India function is an essential step. Conservation leaders need to share a clear, long-term vision; be willing to engage in hands-on management; be able and willing to switch between thinking in the big picture and in details; and be willing to encourage learning, improvement, and receptiveness to alternative solutions. We can think of those who have joined the fight to save the last wild tigers as Visionaries > as Change-Agents > as Caretakers > as Undertakers. We can be visionaries but the slide from caretaker to undertaker can be remarkably quick as we witnessed with the loss of the Bali tiger, Caspian tiger, Javan tiger, South China tiger, and the Southeast Asian tigers in Vietnam, Laos, and Cambodia. Here in India, in the Sariska and Panna tiger reserves, conservationists successfully reversed the process from being undertakers to becoming visionaries and agents of tiger recovery. This is a great shift in thinking, a shift for the tiger's future in India and throughout its range. It is transformational in the young field of conservation biology. But this approach is not a substitute for maintaining and restoring habitat connectivity. Translocation of tigers into established, high-density tiger social land-tenure systems as a way to maintain gene flow can led to tiger deaths as my colleagues and I learned when we translocated a conflict tiger into the Sundarbans Tiger Reserve 40 years ago (Seidensticker et al. 1976).

Conclusions

No protected area alone in the CILC is large enough to support an isolated tiger population in the long-term. The persistence of tiger populations, and biodiversity resilience generally, is contingent on maintaining and recovering connectivity through corridors linking protected areas over the entire CILC. Modeling suggests a short time line for tiger survival in isolated reserves because those isolated populations are expected to blink out because of inbreeding depression or from other stochastic events, such as overwhelming poaching episodes. The good news is that three empirical studies replicate the finding that there still is significant gene flow among tigers through the protected area and informal corridor systems in the Central Indian Highlands and through much of the CILC as a whole. However, the fabric of the corridor system is stretched thin with the tiger

populations in the northern protected areas in the CILC now disconnected from those protected areas in the center and southern reaches, and there has been a 47–70 % reduction in effective dispersal between the main source populations—the Kanha and Pench tiger reserves—and other tiger reserves in the south. Tiger habitat occupancy decreased by 20 % between 2006 and 2010 in the CILC. There are nearly 50 pinch points in the habitat linkages in where tiger movement is restricted because of highway, rail lines, mining, human habitation, and other factors and many more are planned in Central India with little or no consideration as to how this infrastructure will impact the persistence of tiger populations and biodiversity resilience. India has important policy tools to support biodiversity resilience by maintaining and recovering landscape connectivity, but their implementation is constrained by the reigning land-management paradigm that separates conservation from development rather than mainstreaming species and habitat conservation into the rural development agenda. I suggest the greatest need moving forward is to scale up from isolated conservation interventions to collective impacts that unite supportive government partners with individuals, NGOs, and economic interests to achieve viable long-term relationships in human and natural systems to value, maintain, and recover landscape connectivity. Our goal is the long-term persistence of tigers and other wildlife and the sustainability of this biodiverse landscape. The other option is the unthinkable—a Central Indian Highlands without tigers. That would be as inconceivable as a clear night sky without stars.

References

Black SA, Groombridge JJ, Jones CG (2011) Leadership and conservation effectiveness: finding a better way to lead. Conserv Lett 4:329–339. doi:10.1111/j.1755-263X.2011.00184.x

Bocetti CI, Goble DD, Scott JM (2012) Using conservation management agreements to secure post-recovery perpetuation of conservation-reliant species: the Kirkland's warbler as a case study. Bioscience 62:874–879. doi:10.1525/bio.2012.62.10.7

Chapron G, Miquelle DG, Lambert A, Goodrich JM, Legendre Colbert J (2008) The impact on tigers of poaching versus prey depletion. J Appl Ecol 45:1667–1674. doi:10.1111/j.1365-2664.2008.01538.x

Crooks KR, Sanjayan M (eds) (2006) Connectivity conservation. Cambridge University Press, Cambridge

Darmania RJ, Seidensticker J, Whitten T, Sethi G, Mackinnon K, Kiss A, Kushlin A (2008) The future of wild tigers. The World Bank, Washington DC. http://siteresources.worldbank.org/SOUTHASIAEXT/resources/Publication/448813-1212785337028/tiger2008.pdf

Dasgupta S, Hammer D, Kraft R, Wheller D (2014) *Vyaghranomics* in space and time: estimating habitat threats for Bengal, Indochinese, Malayan and Sumatran tigers. J Policy Model 36:433–453. doi:10.1016/j.jpolmod.2014.01.014

Dinerstein E, Loucks C, Wikramanayake E, Ginsberg J, Sanderson E, Seidensticker J, Forrest J, Bryja G, Heydlauff A, Klenzendorf S, Leimgruber R, Mills J, O'Brien T, Shrestha M, Simons R, Songer M (2007) The fate of wild tigers. Bioscience 57:508–514

Dinerstein E, Varma K, Wikramanayake E, Powell G, Lumpkin S, Naidoo R, Korchinsky M, Del Valle C, Lohani S, Seidensticker J, Joldersma D, Lovejoy T, Kushlin A (2013) Enhancing conservation, ecosystem services, and local livelihoods through a wildlife premium mechanism. Conserv Biol 27:14–23. doi:10.1111/j.1523-1739.2012.01959.x

Dunbar Brander AA (1923) Wild animals in Central India. Edward Arnold, London

Dutta T, Sharma S, Maldonado JE, Panwar HS, Seidensticker J (2015a) Genetic variation, structure, gene flow in a sloth bear (*Melursus ursinus*) meta-population in the Satpura–Maikal landscape of Central India. PLoS One 10(5):e0123384. doi:10.1371/journal.pone.0123384

Dutta T, Sharma S, Roy PS, McRae B, DeFries R (2015b) Connecting the dots: mapping habitat connectivity for tigers in central India. Reg Environ Change. doi:10.1007/s10113-015-0877-z

Eisenberg JF, Seidensticker J (1976) Ungulates in Southern Asia: a consideration of biomass estimates for selected habitats. Biol Conserv 10:293–308

Forsyth J (1919) The highlands of central India: notes on their forests and wild tribes, natural history and sports. Hall and Chapman, London

Foster DR, Donahue BM, Lambert KF, Hunter ML, Hall BR, et al. (2010) Wildlands and woodlands: a vision for the New England landscape. Harvard University Press, Cambridge Mass. ISBN 978-1-4507-0603-2-50500

Frankham R, Ballou JD, Briscoe DA (2010) Introduction to conservation genetics, 2nd edn. Cambridge University Press, Cambridge

Gilbert M, Miquelle GD, Goodrich JM, Reeve R, Cleaveland S, Matthews L, Joly DO (2014) Estimating the potential impact of canine distemper virus on the Amur tiger population (*Panthera tigris altaica*) in Russia. PLoS One 9(10):e110811. doi:10.1371/journal.pone.0110811

GTI, Global Tiger Initiative Secretariat (2011) Global Tiger Recovery Program 2010–2022. http://globaltigerinitiative.org/publication/global-tiger-recovery-program-2010-2022/

Goodrich J, Miquelle DG, Simirov EN, Kerley LL, Quigley HB, Hornocker MG (2010) Spatial structure of Amur (Siberian) tigers (*Panthera tigris altaica*) on the Sikhote-Alin Biosphere Zapovednick, Russia. J Mammal 91:737–748. doi:10.1644/09-MAMM-A.293.1

Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova A, Tyukavina A, Thau D, Stehman SV, Goetz SJ, Loveland TR, Kommareddy A, Egorov A, Chini L, Justice CO, Towmshend JRG (2013) High-resolution global maps of 21st-century forest

cover change. Science 234:850–852. doi:10.1126/science.1244693

Hayward MW, Jedrzejewski W (2012) Prey preferences of the tiger *Panthera tigris*. J Zool 286:221–231. doi:10.1111/j.1469-7998.2011.00871.x

Jena J, Borah J, Dave C, Vattakaven J (2011) Lifeline for tigers: status and conservation of the Kanha–Pench corridor. WWF-India, New Delhi

Jhala YV, Qureshi Q, Gopal R, Sinha PR (eds) (2011) Status of tigers, co-predators, and prey in India, 2010. National Tiger Conservation Authority, GOI, New Delhi, Wildlife Institute of India, Dehradun

Joshi A, Vaidyanathan S, Modol S, Edgaonkar A, Ramakrishnan U (2013) Connectivity of tiger (*Panthera tigris*) populations in the human-influenced forest mosaic of Central India. PLOS One 8(11):e77980. doi:10.1371/journal.pone.0077980

Kania J, Kramer M (2011) Collective impact. Stanford Soc Innov Rev Winter 2011:36–41

Karanth KU, Nichols JD, Kumar NS, Link WA, Hines JE (2004) Tigers and their prey: predicting carnivore densities from prey abundance. PNAS (USA) 101:4854–4858. doi:10.1073/pnas.0306210101

Karanth KK, Gopalaswamy AM, DeFries R, Ballal N (2012) Assessing patterns of human-wildlife conflict and compensation around a central India protected area. PLoS One 7(12):e50433. doi:10.1371/journal.pone.0050433

Kenney J, Smith JLD, Starfield AM, McDougal C (1995) The long-term effects of tiger poaching on population viability. Conserv Biol 9:1127–1133

Kenney J, Allendorf FW, McDougal C, Smith JLD (2014) How much gene flow is needed to avoid inbreeding depression in wild tiger populations? Proc R Soc B 281:20133337. doi:10.1098/rspb.2013.3337

Laurance WF, Sayer J, Cassman KG (2014) Agricultural expansion and its impacts on tropical nature. Trends Ecol Evol 29:107–116. doi:10.1016/j.tree.2013.12.001

Miller JRB (2014) Live and let live. Frontline www.frontline.in/environment/live-and-let-live/article6141070.ece

Miller CS, Hebblewhite M, Petrunenka YK, Seryodkin IV, Goodrich JM, Miquelle DG (2014) Amur tiger (*Panthera tigris altaica*) energetic requirement: implications for conserving wild tigers. Biol Conserv 170:120–129. doi:10.1016/j.biocon.2013.12.012

Miquelle DG, Goodrich JM, Smirnov EV, Stephens PA, Zaumyslova Chapron G, Kerley L, Murzin AA, Hornocker MG, Quigley HB (2010) Amur tigers: a case study of tigers living on the edge. In: Macdonald DW, Loveridge AJ (eds) Biology and conservation of wild felids. Oxford University Press, Oxford, pp 325–329

Mukerjee M (2014) Tigers or coal? India makes a choice. Huffington Post. http://www.huffingtonpost.com/madhusree-mukerjee/tigers-or-coal-india-make_b_4593537.html

Noss RF, Daly KM (2006) Incorporating connectivity into broad-scale conservation planning. In: Crooks KR, Sanjayan M (eds) Connectivity conservation. Cambridge University Press, Cambridge, pp 587–619

Padma TV (2013) India faces uphill battle on biodiversity. Nature 504:200. doi:10.1038/504200a

Panwar HS (1987) Project tiger: the reserves, the tigers and their future. In: Tilson RL, Seal US (eds) Tigers of the world: the biology, biopolitics, management, and conservation of an endangered species. Noyes Publications, Park Ridge, pp 110–117

Quintero JD, Roca R, Morgan A, Mathur A, Shi X (2010) Smart green infrastructure in tiger range countries: a multi-level approach. The World Bank, Washington DC. http://documents.worldbank.org/curated/en/2010/09/12887165/smart-green-infrastructure-tiger-range-countries-multi-level-aproach

Qureshi Q, Saini S, Basu P, Raza R, Jhala Y (2014) Connecting tiger populations for long-term conservation. TR2014-02. National Tiger Conservation Authority & Wildlife Institute of India, Dehradun

Rangarajan M (1996) Fencing the forest: conservation and ecological change in India's Central Provinces. Oxford University Press, New Delhi

Rathore CS, Dubey Y, Shrivastava A, Pathak P, Patil V et al (2012) Opportunities of habitat connectivity for tigers (*Panthera tigris*) between Kanha and Pench National Parks in Madhya Pradesh, India. PLOS One 7(7):e39996. doi:10.1371/journal.pone.0039996

Redford KH, Amato G, Baillie J, Beldomenico P, Bennett EL, Clum N, Cook R, Fonseca G, Hedges S, Launay F, Lieberman S, Mace GM, Murayama A, Putnam A, Robinson JG, Rosenbaum H, Sanderson EW, Stuart SN, Thomas P, Thorbjarnarson J (2011) What does it mean to successfully conserve a (vertebrate) species? Bioscience 61:39–48. doi:10.1525/bio.2011.61.1.9

Richards JF (2003) The unending frontier: an environmental history of the Early Modern World. University of California Press, Berkeley

Ripple WJ, Estes JA, Beschta RL, Wilmers CC, Ritchie EG, Hebblewhite M, Berger J, Elmhagen B, Letnic M, Nelson MP, Schmitz OJ, Smith DW, Wallach AD, Wirsing AJ (2014) Status and ecological effects of the world's largest carnivores. Science 343:1241484. doi:10.1126/science.1241484

Rogers WA, Panwar HS (1988) Planning a wildlife protected network in India, vol II. Project FO: IND/82/003. FAO, Dehradun

Sanderson EW, Forrest J, Loucks C, Ginsberg J, Dinerstein E, Seidensticker J, Leimgruber P, Songer M, Heydlauff A, O'Brien T, Bryja G, Klenzendorf S, Wikramanayake E (2010) Setting priorities for tiger conservation: 2005–2015. In: Tilson R, Nyhus PJ (eds) Tigers of the world: the science politics, and conservation of *Panthera tigris*. Academic Press, New York, pp 143–161

Sayer J, Sunderland W, Ghazoul J, Pfund JL, Djeil D, Meijaard E, Venter M, Boedhiartono AK, Day M, Garcis C, Van Oosten C, Buck LE (2013) Ten principals for a landscape approach to reconciling agriculture, conservation, and other competing land uses. PNAS (USA) 110:8349–8835. doi:10.1073/pnas.1210595110

Schaller GB (1967) The deer and the tiger: a study of wildlife in India. University of Chicago Press, Chicago

Seidensticker J (2010) Saving wild tigers: a case study in biodiversity loss and challenges to be met for recovery beyond 2010. Integr Zool 5:285–299. doi:10.1111/j.1749-4877.2010.00214.x

Seidensticker J, Lahiri RK, Das KC, Wright A (1976) Problem tiger in the Sundarbans. Oryx 8:267–273

Seidensticker J, Dinerstein E, Goyal SP, Gurung B, Harihar A, Johnsingh AJT, Manandhar A, McDougal CW, Pandav B, Shrestha M, Smith JLD, Sunquist M, Wikramanayake E (2010) Tiger range collapse and recovery at the base of the Himalayas. In: Macdonald DW, Loveridge AJ (eds) Biology and conservation of wild felids. Oxford University Press, Oxford, pp 305–323

Shames S, Clarvis MH, Kissinger G (2014) Financing strategies for integrated landscape investment. EcoAgriculture Partners, on behalf of the Landscapes for People Initiative, Washington DC. http://landscape.ecoagriculture.org/globalreview/financingstrategies

Sharma S, Dutta T, Maldonado JE, Wood TC, Panwar HS, Seidensticker J (2013a) Spatial genetic analysis reveals high connectivity of tiger (*Panthera tigris*) populations in Satpura–Maikal landscape of Central India. Ecol Evol 3:48–60. doi:10.1002/ece3.432

Sharma S, Dutta T, Maldonado JE, Wood TC, Panwar HS, Seidensticker J (2013b) Forest corridors maintain historical gene flow in a tiger metapopulation in the highlands of central India. Proc R Soc B 280:20131506. doi:10.1098/rspb.2013.1506

Simcharoen A, Savini T, Gale GA, Simcharoen S, Duangchantrasiri S, Pakpien S, Smith JLD (2014) Female tiger *Panthera tigris* home range size and prey abundance: important metrics for management. Oryx 48:370–377. doi:10.1017/S0030605312001408

Singh R, Qureshi Q, Snakar K, Krausman PR, Goyal SP (2013) Use of camera traps to determine dispersal in tigers in semi-arid landscapes, western India. J Arid Envir 98:1–4. doi:10.1016/j.jaridenv.2013.08.005

Smith JLD (1993) The role of dispersal in structuring tiger populations. Behaviour 124:165–195

Standish RJ, Hobbs RJ, Mayfield MM, Bestelmeyer BT, Sding KN, Battaglia LL, Eviner V, Hawkes CV, Temperton VM, Cramer VA, Harris JA, Funk JL, Thomas PA (2014) Resilience in ecology: abstraction, distraction or where the action in? Biol Conserv 177:43–51. doi:10.1016/j.biocon.2014.06.008

Sunquist ME (1981) The social organization of tigers (*Panthera tigris*) in Royal Chitwan National Park, Nepal. Smithson Contrib Zool 336:1–98

Task Force, Indian Board for Wild Life (1972) Project tiger: a planning proposal for preservation of tiger (*Panthera tigris tigris* Linn.) in India. New Delhi: Indian Board for Wild Life, Ministry of Agriculture, GOI, New Delhi

Thapar V (2003) Battling for survival: India's wilderness over two centuries. Oxford University Press, New Delhi

Thompson JR, Wiek A, Swanson FJ, Carpenter SR, Fresco N, Holllingsworth T, Spies TA, Foster DR (2012) Scenario studies as synthetic and integrative research activity for long-term ecological research. Bioscience 62:367–376. doi:10.1525/bio.2012.62.4.8

Traill LW, Brook BW, Frankham RR, Bradshaw CJA (2010) Pragmatic population viability targets in a rapidly changing world. Conserv Biol 143:28–34. doi:10.1016/j.biocon.2009.09.001

Van Brouwershaven R (2014) The Africa landscapes action plan. http://beta.landscapes.ecoagriculture.org/wp-content/uploads/sites/4/2014/09/African-Landscapes-Action-Plan-FINAL-FINAL.pdf

Wikramanayake E, Dinerstein Loucks C, Olson DM, Morrison J, Lamoreux J, McNight M, Hedao P (2002) Terrestrial ecoregions of the Indo-Pacific: a conservation assessment. Island Press, Washington DC

Wikramanayake E, Dinerstein E, Forrest J, Loucks C, Seidensticker J, Klenzendorf S, Sanderson EW, Simons R, Heydlauff A, Ginsberg J, O'Brien T, Leimgruber P, Songer M, Bryja G (2010) Road to recovery or catastrophic loss: how will the next decade end for wild tigers? In: Tilson R, Nyhus PJ (eds) Tigers of the world: the science politics, and conservation of *Panthera tigris*. Academic Press, New York, pp 493–506

Wikramanayake E, Dinerstein E, Seidensticker J, Lumpkin S, Pandav B, Shrestha M et al (2011) A landscape-based conservation strategy to double the wild tiger population. Conserv Lett 4:219–227. doi:10.1111/j.1755-263X.2010.00162.x

Yumnam B, Jhala YV, Qureshi Q, Maldonado JE, Gopal JE, Saini S, Fleischer RC (2014) Prioritizing tiger conservation through landscape genetics and habitat linkages. PLoS One 9(11):e111207. doi:10.1371/journal.pone.0111207