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What does the recovery debt really measure?

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Recently, Moreno-Mateos et al. (2017) coined the concept 'recovery debt', clearly a close relative of the ecosystem service debt (Isbell et al. 2015), and gave it significance as "*the interim reduction of biodiversity and biogeochemical functions occurring during ecosystem recovery*". Using rather impressive dataset consisting 3,035 sampling plots worldwide as an example, they analysed the recovery debt for plant and animal species diversity and abundance as well as for carbon and nitrogen cycling. Based on their analysis Moreno-Mateos et al. conclude that "… *recovering and restored ecosystems have less abundance, diversity and cycling of carbon and nitrogen than 'undisturbed' ecosystems …*". Here, we scrutinize the proposed new concept and point out problems in conclusions resulting from the operationalization of the concept.

An undesired change in biodiversity, ecosystem functions or services due to anthropogenic disturbance is customarily called degradation. Magnitude of degradation can be estimated as the difference between the current state of the ecosystem and its undisturbed natural state (UNEP 2003; Bull et al. 2014; Kotiaho et al. 2016a, b) (Fig. 1a). Moreno-Mateos et al. suggest that the recovery debt could be a useful indicator of the magnitude of degradation. They first derive an equation for an absolute recovery debt over any given time period (RD) and then state that as there is variation in the time period of different studies, it is preferable to express the recovery debt in per annum terms (RDt). Thus, while the customary measure of the magnitude of degradation is calculated for the current state of the ecosystem, the recovery debt (RDt)

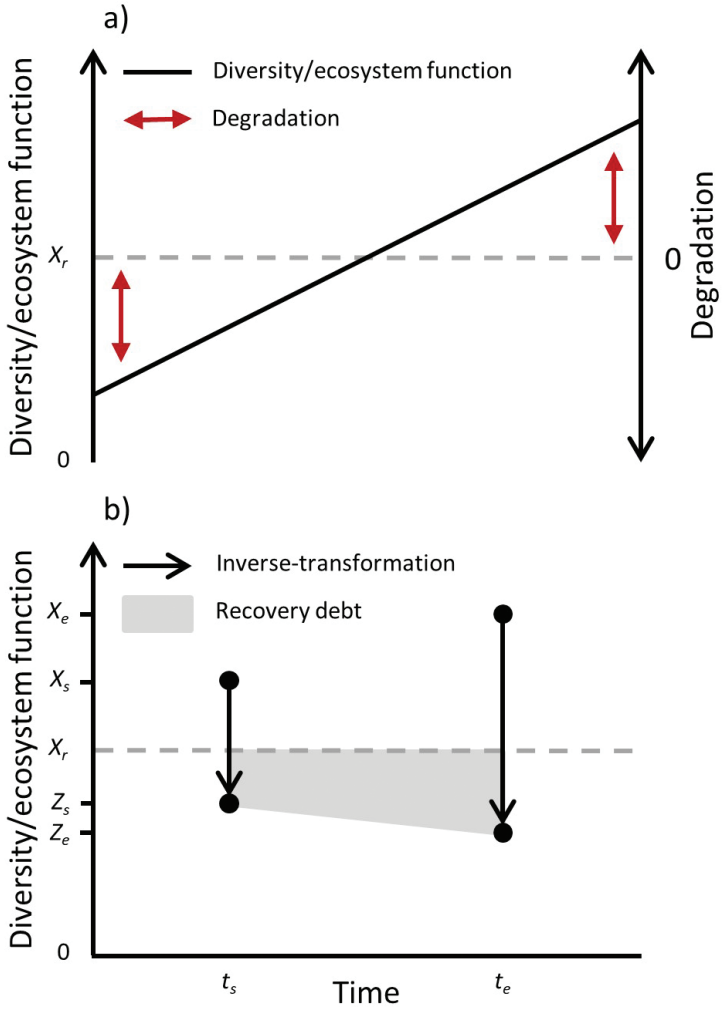

Figure 1. A schematic figure describing how degradation and the recovery debt are estimated in relation to undisturbed and disturbed ecosystem states. a) The difference between diversity/ecosystem function and the magnitude of degradation relative to an undisturbed natural state reference. While diversity/ecosystem function can decrease or increase due to anthropogenic disturbance relative to the undisturbed reference state (X_r, grey dashed line), both lower and higher values than the undisturbed reference state can be considered degradation. It is worth noting, however, that while increase and decrease are neutral descriptors of change, by labelling any deviation from the natural state as degradation we are making a value statement that such change is undesired. b) The influence of the inverse-transformation on the diversity/ecosystem function values and recovery debt. The recovery debt *sensu* Moreno-Mateos et al. (2017) (the interim reduction of biodiversity and ecosystem functions lost during recovery compared to reference values) depends on the inverse-transformation Z_s of the original magnitude of degradation (X_s), the inverse-transformation Z_e of the state achieved during recovery (X_e), the time used for recovery (t_e-t_s), and the undisturbed reference state value (X_r, grey dashed line). For simplicity, the undisturbed reference state of the ecosystem (X_r) is depicted as a static line, although in reality each ecosystem type has a dynamic mean natural state surrounded by some variance.

looks back to the history of the ecosystem and takes an average per annum magnitude of degradation of the past states during the recovery of the ecosystem.

While an effort to estimate the lost ecosystem diversity, functions and services due to delayed recovery is welcome, the significance of the concept is not as intuitive as it first appears. In particular, from the perspective of biodiversity *per se* the meaning of the concept is difficult to perceive. In essence, the recovery debt for diversity can be understood as the absolute number of lost diversity years (RD), or as an average diversity which was absent every year during the recovery process (RDt). Compared to the behaviour of the customary measure of the magnitude of degradation, which declines to zero during complete recovery, the absolute recovery debt (RD) increases until the diversity has reached the reference level and persists unchanged thereafter, while the recovery debt per annum (RDt) asymptotically approaches zero but only in infinity. In such a case, and still focusing exclusively on the diversity *per se*, we do not understand how the recovery debt values that persist after the complete recovery of the ecosystem improve our understanding of the magnitude of degradation of the ecosystem. Therefore, we feel that further clarification of the meaning and importance of the concept is needed before the concept is adopted to be used for diversity.

Nevertheless, as Moreno-Mateos et al. state, "… *shortfalls in biodiversity and ecosystem functionality will affect the quantity and quality of ecosystem services provided by the recovering ecosystems*". Thus, the recovery debt potentially gains its meaning through the perspective of lost anthropogenic benefits. In particular, this might be the case for variables measured per annum basis, such as carbon sequestration, recovery debt being the amount of carbon remaining in the atmosphere due to the lost sequestration during the recovery process.

Unfortunately, the way the recovery debt is operationalised makes the measure ambiguous also in terms of the ecosystem services. In the methods, Moreno-Mateos et al. state that there were many cases, apparently nearly half of the data, where the starting values of the measured response variables for the recovering ecosystems were greater than those in the reference ecosystems and continue: "*in these cases, we assumed that response values above the reference value represent negative effects, and thus [such response values] were inverse-transformed using the formula* $Z_{s,e} = X_r*(X_r/X_{s,e})$". This calculation transforms the values that are greater than the reference to become smaller than the reference (Fig. 1b). Moreover, the same logic was used if the recovery debt per annum value was larger than the undisturbed reference. If we now reconsider the example we made with carbon sequestration above, it becomes clear that the operationalization of the recovery debt makes it ambiguous. If carbon sequestration in reality is greater than the reference but is inverse-transformed to be lower than the reference, then recovery debt confounds the truly increased sequestration with the truly decreased sequestration and can not be used to infer whether there is more or less carbon remaining in the atmosphere after the recovery period. Thus, contrary to the concept of e.g. carbon debt (Fargione et al. 2008) "repayment" of the recovery debt is impossible.

What the recovery debt really quantifies is the interim *deviation* rather than *reduction* of biodiversity and ecosystem functions from undisturbed state. These two are

obviously very different things. The ambiguity seems to be reflected in the way the recovery debt values are constantly referred as 'reductions' or 'deficits' of biodiversity and functions. However, the reason why all the data appear as reductions is the inverse-transformation. Therefore, the contrast to previous studies showing that α-diversity does not change through time (Vellend et al. 2013; Dornelas et al. 2014) is hardly surprising given that in the cited studies no inverse-transformation was made.

As such the inverse-transformation relative to the undisturbed natural reference state has an interesting underlying assumption: every focal location has its own characteristic diversity and ecosystem functions, and any deviation from this is degradation – be it increased or reduced diversity or function (Fig. 1a). The use of undisturbed natural state of an ecosystem as a baseline or reference for measuring anthropogenic degradation is the only scientifically justifiable choice since an arbitrarily chosen baseline might yield biased inferences in the magnitude and direction of degradation (Gonzalez et al. 2016; Kotiaho et al. 2016a). However, there is also another underlying assumption in the recovery debt as operationalized by Moreno-Mateos et al., and that is, that the undisturbed natural state reference is simultaneously the target of the recovery. While this is a rather traditional view in ecological restoration, and indeed often the undisturbed state is an appropriate target for restoration, it is nevertheless worth noting that making undisturbed state as an exclusive target against which the success of restoration is measured is an ideology. While undisturbed natural state reference is fundamental for determining the magnitude of anthropogenic degradation, target is a political decision balancing between economic, social and ecological considerations.

AUTHOR CONTRIBUTION

ME and JSK conceived the ideas and drafted the manuscript. TH and SK critically commented on the manuscript and developed the ideas further.

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Authors	Contribution	ACI
ME	0.40	2.00
JSK	0.40	2.00
TH	0.10	0.33
SK	0.10	0.33

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