REVIEW ARTICLE

Undertaking large-scale forest restoration to generate ecosystem services

David Lamb[1,2,3,4]

The global community is seeking to substantially restore the world's forest cover to improve the supply of ecosystem services.

Table 1. The relationship between increasing tree species richness, the traits of these species, and the provisioning of ecosystem services.

a higher level of species richness is also an advantage when the objective is to improve landscape aesthetics or provide recreational opportunities. Between these two patterns are a large number of ecosystem services that can be supplied by restoring some, but not necessarily all, of the former species richness. In most cases, the supply of these services increases in proportion to any increase in species richness (indicated by line B in Fig. 1). Examples of these relationships are soil conservation, watershed protection, and the restoration of soil fertility. Not all of the relationships are clear and many are also in uenced by species traits, the relative proportions of species used in planting mixtures as well as by planting densities (which affect the extent of understory development). The landscape context is also important (see further below).

An example of the uncertainties in these relationships is provided by the relationship between diversity and hydrological processes. Annual water yields and dry season ows are often of major concern to those undertaking restoration. But the in uence of species richness on hydrological processes is complicated; any kind of restoration will increase evapotranspiration and diminish stream ows but, at the same time, restoration of severely degraded lands may also improve water in ltration rates, increase groundwater stores, and reduce overland ows. The impact on base ow and whether or not dry season stream ow improves then depends on the relative importance of these two processes (Bruijnzeel 2004). Some evidence suggests that multispecies plantings may use more water than monocultures and thus reduce both annual and seasonal water ows (Table 1). But other studies have not found this relationship. Likewise, the effect of multispecies plantings on the in ltration capacity of soils also remains unclear (Table 1). However, the net impact depends as well on the proportions of different species used and their transpiration rates, differences in growth rates and rates of rainfall interception by canopies and litter, as well as differences in understory biomass and the way forests are managed (Lacombe et al. 2015). Finally, hydrological relationships are also in uenced by location and scale (see further below). In summary, it is possible that planting a simple species mixture may improve dry season ow in heavily degraded sites but, more generally, it seems that hydrological ows are not as strongly in uenced by species richness as by a variety of other factors. The issue obviously deserves further investigation.

These same uncertainties also exist in our understanding of the processes underlying the delivery of many other ecosystem services as well (Birkhofer et al. 2015). Re ecting this, the relationships in Table 1 are shown as A–B, B–C, or A–B–C depending on the evidence that is currently available. This means that, of the 12 ecosystem services reviewed, there was evidence for relationship A in 8 cases, for relationship B in 9 cases, and relationship C in 5 cases. In short, relatively modest numbers of tree species are likely to generate a number of ecosystem services although different species may be more effective than others depending on their traits and on the service required. But the evidence also suggests a wider variety of ecosystem services will be generated when a larger number of species are used. Interestingly, van der Plas et al. (2016) have noted that more species can generate a greater degree of multifunctionality when only moderate levels of functioning are required but that this diversity may be negatively related when higher levels of functioning are required for certain services. Again, much depends on the species traits.

Spatial Location of Restoration and the Generation of Ecosystem Services

Despite the prominence given in the literature to biodiversity–ecological functioning relationships, the diversity of tree species is not the only factor in uencing the extent to which restoration generates ecosystem services. Locations are also important because landscapes are not uniform and some locations are more critical than others for certain ecosystem services (Table 2). Note that some of these critical sites may occupy a large proportion of a particular landscape (e.g. steep lands) while others, though functionally important, may occupy only small areas.

The spatial location of restoration is obviously important for reducing erosion but it is also in uences hydrological ows. For example, in subhumid areas, tree planting on foot slopes or in riverine locations has a much larger effect on groundwater use than when carried out at locations further w5ysc9feiw5yspr fruearcesthe and ()01(nalnsity)-3796(byt)-778.6(acelnerating)-378.6levtrnesporation to caetbrdwcatnabis)]TJ 0 -1.2096 TD [(of)-010.3(r(fo(esration)-026.6(c)-0.1

estorationnaurcal (fo(esl)-231r(mnaenes)3230-4cang)-23052(ef)2
J(ines)-365(e)-0.1t. n s p besven to
ocations prbvdcingbisraas of (pecies)-22473((T)79.4(bóns)2743(
vessity
fo(esl)4052.9(and)405241(a)01.1((o)2467(w)4052.9bv)-0.2(itae)402
ol lti9udiocalthdwysn
c to
c1-43uofvt(y)]TJ 0 -1.2096 TD [(includcing the w
effrueat (ocation.e)1964insSgtaens fot
ovthrsf m ecosys-y
()01(lerice

scusssdw624 b9

Table 2. Locations within landscapes where restoration can help generate various ecosystem services.

[illegible]	[illegible]	[illegible]
Control of erosion	Steep slopes	By stabilizing soil surfaces and impeding soil movement (Vanacker et al. 2007; Wang et al. 2012).
Control of sedimentation, improved water quality	Riverine areas	By reducing stream bank erosion and limiting soil and

et al. 2013). Most of these studies separated the year-to-year variation on stream ow from the effects of land cover changes using hydrological modeling approaches but the reliability of such analyses is severely constrained by uncertainties in areal rainfall inputs. As noted earlier, reforestation can also have pos-

and institutions will be needed encourage the use of these new approaches and to facilitate the necessary trade-offs needed to implement them across large landscapes.

Acknowledgments

I am grateful to colleagues J. Aronson, S. Bruijnzeel, R. Chazdon, P. Erskine, and B. Jackson for offering feedback on drafts of the manuscript.

LITERATURE CITED

Asbjornsen H, Hernandez-Santana V, Liebman M, Bayala J, Chen J, Helmers M, Ong C, Schulte LA (2014) Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. Renewable Agriculture and Food Systems 29:101–125

Barral MP, Benayas JMR, Meli P, Maceira NO (2015) Quantifying the impacts of ecological restoration on biodiversity and ecosystem services in agroecosystems: a global meta-analysis. Agriculture, Ecosystems & Environment 202:223–231

Beck H, Bruijnzeel L, Van Dijk A, McVicar T, Scatena F, Schellekens J (2013) The impact of forest regeneration on stream flow in 12 meso-scale humid tropical catchments. Hydrology and Earth System Sciences Discussions 10:3045–3102

Bianchi F, Booij C, Tscharntke T (2006) Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. Proceedings of the Royal Society of London B: Biological Sciences 273:1715–1727

Birkhofer K, Diehl E, Andersson J, Ekroos J, Früh-Müller A, Machnikowski F, Mader VL, Nilsson L, Sasaki K, Rundlöf M (2015) Ecosystem services—current challenges and opportunities for ecological research. Frontiers in Ecology and Evolution 2:87

Bonell M, Purandara B, Venkatesh B, Krishnaswamy J, Acharya H, Singh U, Jayakumar R, Chappell N (2010) The impact of forest use and reforestation on soil hydraulic conductivity in the western Ghats of India: implications for surface and sub-surface hydrology. Journal of Hydrology 391:47–62

Bonn Challenge (2014) The challenge: a global effort. http://www.bonnchallenge.org/content/challenge (accessed 17 Feb 2017)

Booth TH (2012) Forest landscape restoration in Australia's Murray-darling basin. Pages 355–371. In: Stanturf JA, Madsen P, Lamb D (eds) A goal-orientated approach to forest landscape restoration. Springer, Dordrecht, the Netherlands

Brancalion P, Viani R, Calmon M, Carrascosa H, Rodrigues R (2013) How to organize a large-scale ecological restoration program? The framework developed by the Atlantic Forest restoration pact in Brazil. Journal of Sustainable Forestry 32:728–744

Brockerhoff EG, Jactel H, Parrotta JA, Quine CP, Sayer J (2008) Plantation forests and biodiversity: oxymoron or opportunity? Biodiversity and Conservation 17:925–951

Brose U, Hillebrand H (2016) Biodiversity and ecosystem functioning in dynamic landscapes. Philosophical Transactions of the Royal Society B 371:1694

Bruijnzeel LA (2004) Hydrological functions of tropical forests: not seeing the soil for the trees? Agriculture, Ecosystems and Environment 104:185–228

Budiharta S, Meijaard E, Wells JA, Abram NK, Wilson KA (2016) Enhancing feasibility: incorporating a socio-ecological systems framework into restoration planning. Environmental Science and Policy 64:83–92

Carrus G, Scopelliti M, Lafortezza R, Colangelo G, Ferrini F, Salbitano F, Agrimi M, Portoghesi L, Semenzato P, Sanesi G (2015) Go greener, feel better? The positive effects of biodiversity on the well-being of individuals visiting urban and peri-urban green areas. Landscape and Urban Planning 134:221–228

Carwardine J, Hawkins C, Polglase P, Possingham HP, Reeson A, Renwick AR, Watts M, Martin TG (2015) Spatial priorities for restoring biodiverse carbon forests. Bioscience 65:372–382

CBD (Convention on Biological Diversity) (2011) Ways and means to support ecosystem restoration. UNEP Convention on Biological Diversity, Montreal, Canada. https://www.cbd.int/doc/meetings/sbstta/sbstta-15/official/sbstta-15-04-en.pdf

Chazdon RL, Uriarte M (2016) Natural regeneration in the context of large-scale forest and landscape restoration in the tropics. Biotropica 48:709–715

Chetkiewicz C, St Clair CC, Boyce MS (2006) Corridors for conservation: integrating pattern and process. Annual Review of Ecology, Evolution, and Systematics 37:317–342

Chokkalingam U, Zhou Z, Wang C, Toma T (eds) (2006) Learning lessons from China's forest rehabilitation efforts. Center for International Forestry Research, Bogor, Indonesia

Conti G, Díaz S (2013) Plant functional diversity and carbon storage–an empirical test in semi-arid forest ecosystems. Journal of Ecology 101:18–28

Cork SJ, Hume ID, Foley WJ (2000) Improving habitat models and their utility in koala conservation. Conservation Biology 14:660–668

Crouzeilles R, Curran M (2016) Which landscape size best predicts the influence of forest cover on restoration success? A global meta-analysis on the scale of effect. Journal of Applied Ecology 53:440–448

Dallimer M, Irvine KN, Skinner AM, Davies ZG, Rouquette JR, Maltby LL, Warren PH, Armsworth PR, Gaston KJ (2012) Biodiversity and the feel-good factor: understanding associations between self-reported human well-being and species richness. Bioscience 62:47–55

De Jong W, Sam DD, Hung TV (2006) Forest rehabilitation in Vietnam: history, realities and future. Center for International Forestry Research, Bogor, Indonesia

de Souza Leite M, Tambosi LR, Romatelli I, Metzger JP (2013) Landscape ecology perspective in restoration projects for biodiversity conservation: a review. Natureza & Conservação 11:108–118

Feld CK, Birk S, Bradley DC, Hering D, Kail J, Marzin A, Melcher A, Nemitz D, Pedersen ML, Pletterbauer F (2011) From natural to degraded rivers and back again: a test of restoration ecology theory and practice. Advances in Ecological Research 44:119–209

Feng X, Sun G, Fu B, Su C, Liu Y, Lamparski H (2012) Regional effects of vegetation restoration on water yield across the Loess Plateau, China. Hydrology and Earth System Sciences 16:2617–2628

Filoso S, Bezerra MO, Weiss KCB, Palmer MA (2017) Impacts of forest restoration on water yield: a systematic review. PLoS ONE 12:e0183210

Gei MG, Powers JS (2013) Do legumes and non-legumes tree species affect soil properties in unmanaged forests and plantations in Costa Rican dry forests? Soil Biology and Biochemistry 57:264–272

Genet M, Stokes A, Fourcaud T, Norris JE (2010) The influence of plant diversity on slope stability in a moist evergreen deciduous forest. Ecological Engineering 36:265–275

George S, Harper R, Hobbs R, Tibbett M (2012) A sustainable agricultural landscape for Australia: a review of interlacing carbon sequestration, biodiversity and salinity management in agroforestry systems. Agriculture, Ecosystems and Environment 163:28–36

Giannini T, Giulietti A, Harley R, Viana P, Jaffe R, Alves R, et al. (2017) Selecting plant species for practical restoration of degraded lands using a multiple-trait approach. Austral Ecology 42:510–521

Harrison P, Berry P, Simpson G, Haslett J, Blicharska M, Bucur M, Dunford R, Egoh B, Garcia-Llorente M, Geamănă N (2014) Linkages between biodiversity attributes and ecosystem services: a systematic review. Ecosystem Services 9:191–203

Hobbs R, Higgs E, Harris JA (2009) Novel ecosystems: implication for conservation and restoration. Trends in Ecology and Evolution 24:599–605

Holl KD (2017) Research directions in tropical forest restoration. Annals of the Missouri Botanical Garden 102:237–250

Holl KD, Crone EE, Schultz CB (2003) Landscape restoration: moving from generalities to methodologies. Bioscience 53:491–502

Hulvey KB, Hobbs RJ, Standish RJ, Lindenmayer DB, Lach L, Perring MP (2013) Bene ts of tree mixes in carbon plantings. Nature Climate Change 3:869–874

Ilstedt U, Malmer A, Verbeeten E, Murdiyarso D (2007) The effect of afforestation on water in ltration in the tropics: a systematic review and meta-analysis. Forest Ecology and Management 251:45–51

Jha S, Kremen C (2013) Resource diversity and landscape-level homogeneity drive native bee foraging. Proceedings of the National Academy of Sciences 110:555–558

Johnson CJ (2013) Identifying ecological thresholds for regulating human activity: effective conservation or wishful thinking? Biological Conservation 168:57–65

Jones KR, Watson JE, Possingham HP, Klein CJ (2016) Incorporating climate change into spatial conservation prioritisation: a review. Biological Conservation 194:121–130

Kavanagh RP, Stanton MA, Herring MW (2007) Eucalypt plantings on farms bene t woodland birds in south-eastern Australia. Austral Ecology 32:635–650

Keenan R, Lamb D, Woldring O, Irvine T, Jensen R (1997) Restoration of plant diversity beneath tropical tree plantations in northern Australia. Forest Ecology and Management 99:117–132

Korboulewsky N, Perez G, Chauvat M (2016) How tree diversity affects soil fauna diversity: a review. Soil Biology and Biochemistry 94:94–106

Kremen C, M'Gonigle LK (2015) Small-scale restoration in intensive agricultural landscapes supports more specialized and less mobile pollinator species. Journal of Applied Ecology 52:602–610

Kunert N, Schwendenmann L, Potvin C, Hölscher D (2012) Tree diversity enhances tree transpiration in a Panamanian forest plantation. Journal of Applied Ecology 4.5(440.2(f)]TJ[(pla4406)]TJ -2.4006 -1.3623 TD 0.0001 Tc Lacombe06 -1(Small-scantaty)-2506 -1.3623b[(chanCS93]TJ 2oaPti01 T)0.36J(di)25.1(Ro

Thomson J, Moilanen AJ, Vesk PA, Bennett AF, MacNally R (2009) Where and when to revegetate: a quantitative method for scheduling landscape reconstruction. Ecological Applications 19:817–828

Tscharntke T, Klein AM, Kruess A, Steffan-Dewenter I, Thies C (2005) Landscape perspectives on agricultural intensi cation and biodiversity – ecosystem service management. Ecology Letters 8:857–874

Tobón W, Urquiza-Haas T, Koleff P, Schröter M, Ortega-Álvarez R, Campo J, Lindig Cisneros R, Sarukhán J, Bonn A (2017) Restoration planning to guide Aichi targets in a megadiverse country. Conservation Biology 31:1086–1097

van der Hoek Y, Zuckerberg B, Manne LL (2015) Application of habitat thresholds in conservation: considerations, limitations, and future directions. Global Ecology and Conservation 3:736–743

van der Plas F, Manning P, Allan E, Scherer-Lorenzen M, Verheyen K, Wirth C, et al. (2016) Jack-of-all-trades-effects drive biodiversity-ecosystem multifunctionality relationships in European forests. Nature Communications 7: 11109; https://doi.org/10.1038/ncomms11109

van Dijk AIJM, Keenan RJ (2007) Planted forests and water in perspective. Forest Ecology and Management 251:1–9

van Dijk AIJM, Hairsine PB, Pena Arancibia J, Dowling TI (2007) Reforestation, water availability and stream salinity: a multi-scale analysis in the Murray-Darling Basin, Australia. Forest Ecology and Management 251:94–109

Vanacker V, von Blanckenburg F, Govers G, Molina A, Poesen J, Deckers J, Kubik P (2007) Restoring dense vegetation can slow mountain erosion to near natural benchmark levels. Geology 35:303–306

Vertessy VA, Zhang L, Dawes W (2003) Plantations, river ows and river salinity. Australian Forestry 66:55–61

Vos CC, Berry P, Opdam P, Baveco H, Nijhof B, O'Hanley J, Bell C, Kuipers H (2008) Adapting landscapes to climate change: examples of climate-proof