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The success of woody plant removal depends on encroachment stage and plant traits

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Supplementary Information for

The success of woody plant removal depends on encroachment stage and plant traits

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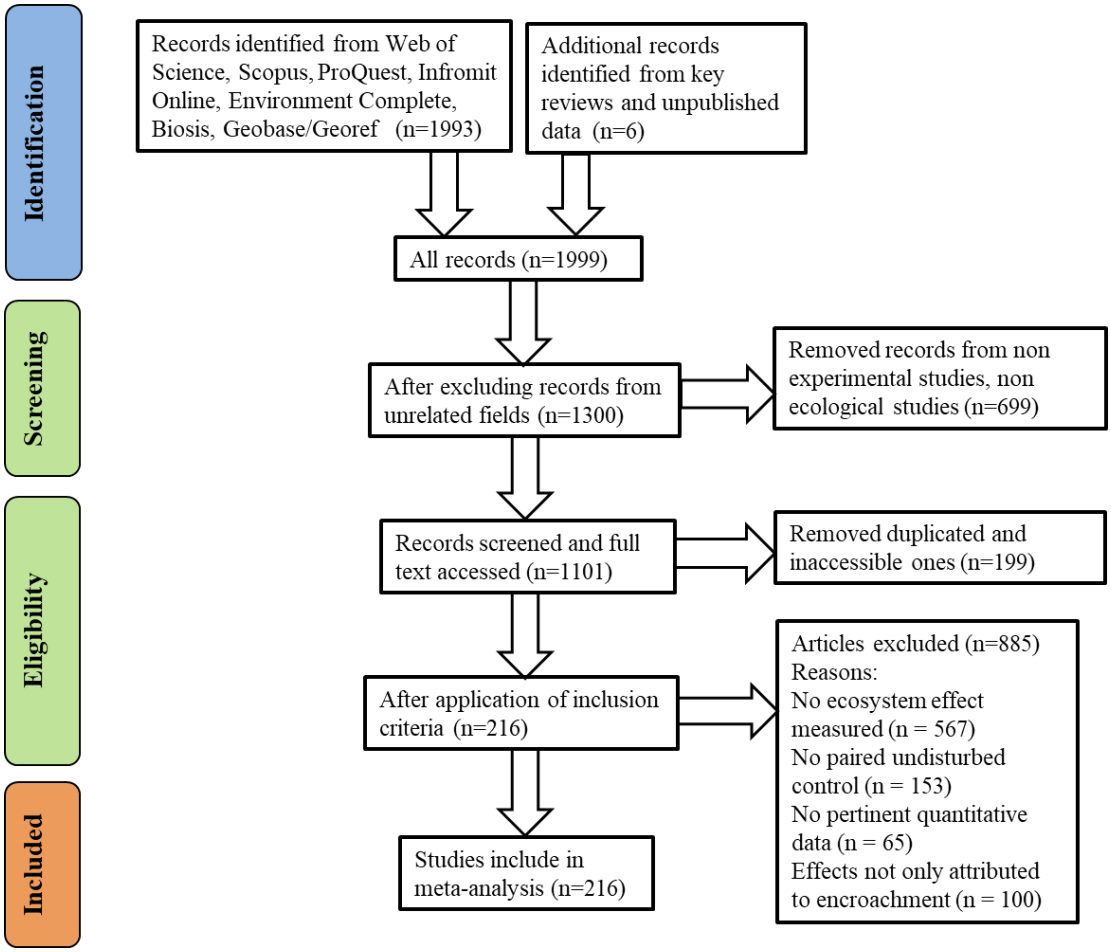
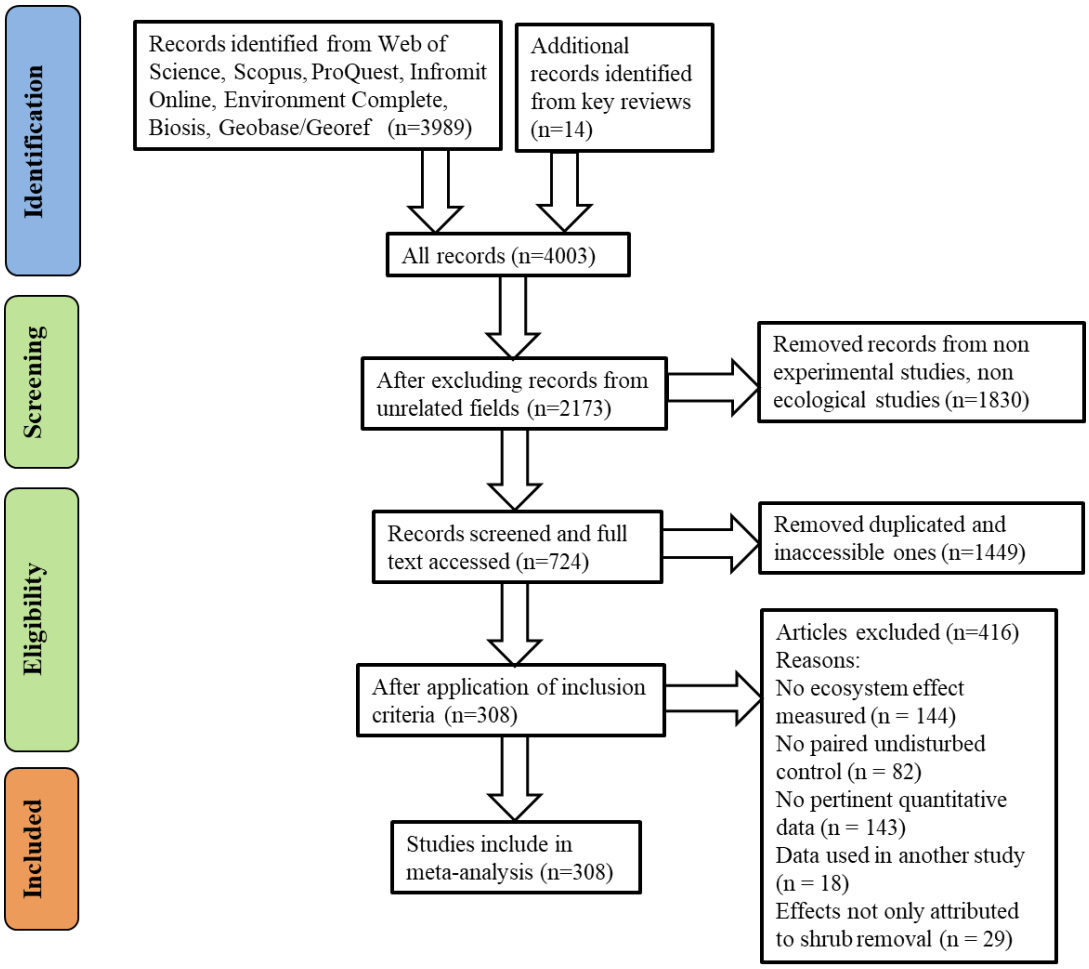
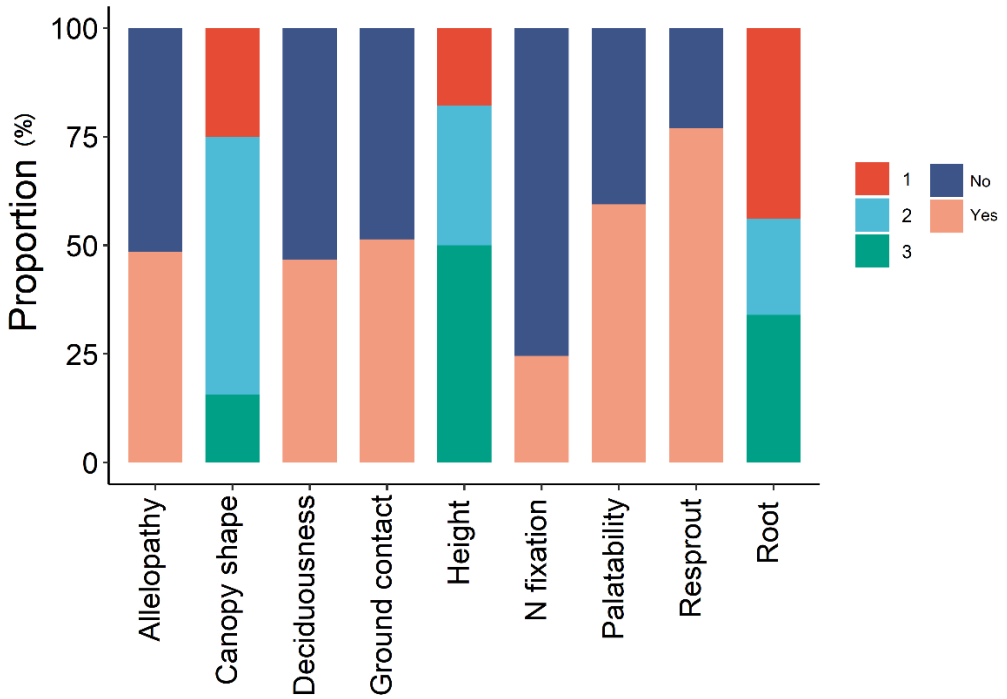
Appendix S1-S4



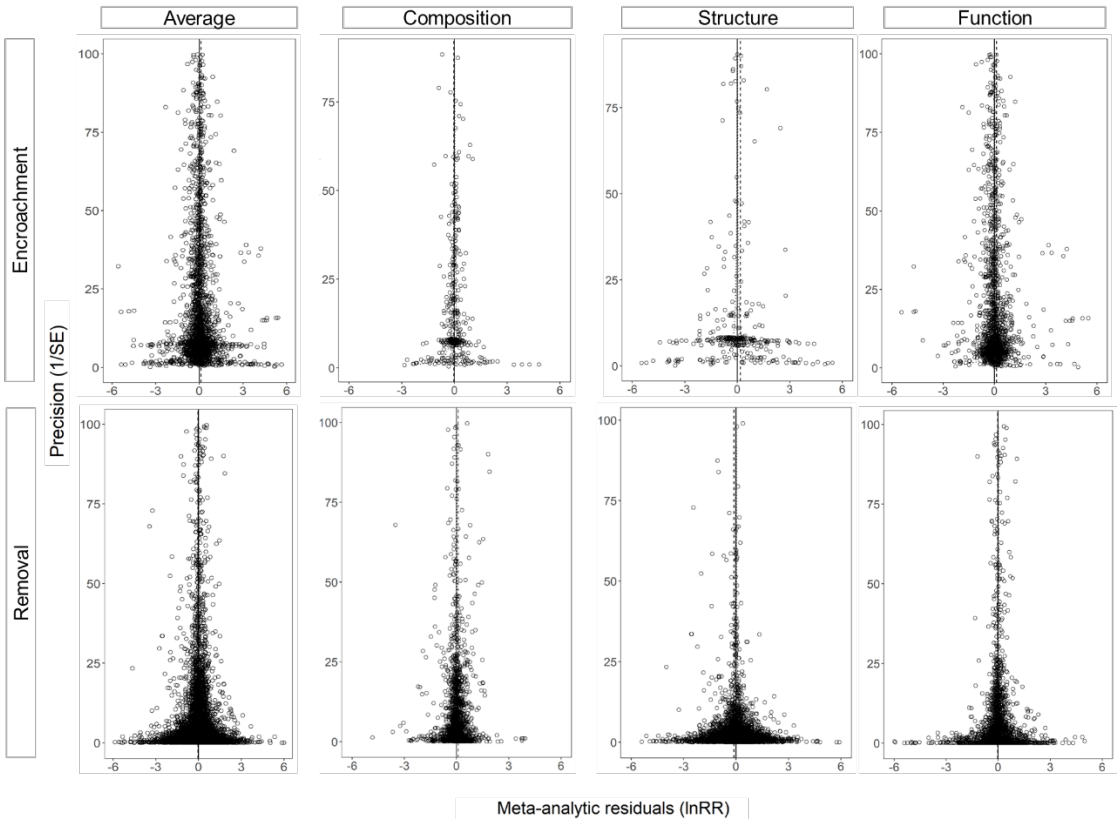
Supplementary Figure 1. Woody encroachment meta-analysis literature searching PRISMA flow diagram



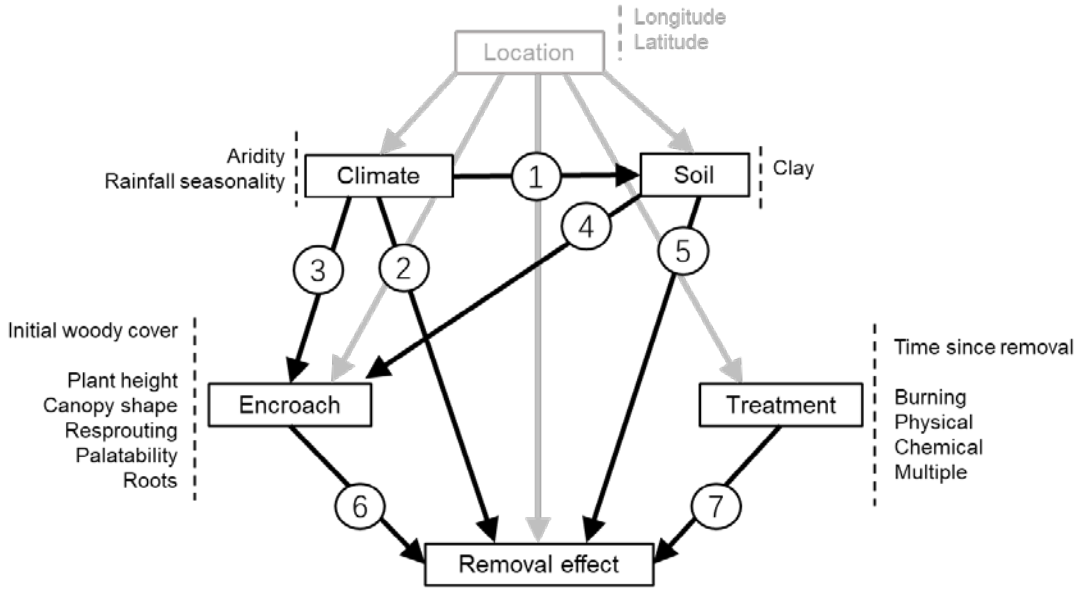
Supplementary Figure 2. Woody plant removal meta-analysis literature searching PRISMA flow diagram



Supplementary Figure 3. The percentage contribution of values of each of the nine plant traits across 213 encroached woody species. To facilitate the quantitatively analysis of plant traits, we ranked the following categorical traits as numeric values, with details shown in Appendix S3. Plant canopy shape: ranked according to a greater ability to obtain resources (water and light) for the understorey, with greater resource accumulation under v-shaped plants but greater rainfall accumulation beneath pyramid-shaped plants (i.e., inverted v-shaped), (v-shaped = 1, weeping/round = 2, pyramid = 3). Height: mean plant height (<1m = 1, 1-3m = 2, >3m = 3). Root type: higher values relate to potentially greater nutrient cycling and water infiltration (tap roots = 1, lateral roots = 2, tap and lateral roots = 3).



Supplementary Figure 4. Funnel plot of precision (inverse of standard error) plotted against effect size residuals for encroachment database and removal database for the average ecosystem response (the whole dataset), ecosystem structure, ecosystem function, and ecosystem composition, respectively.



Supplementary Figure 5. *A priori* model of the predicted direct effects and the indirect effects of climate (aridity, rainfall seasonality) and soil (soil clay content) on the ecosystem response of woody removal, mediated by changes in encroachment characteristics (e.g., the initial woody cover before removal and the traits of the target woody plants). Different removal treatments and time since removal are fixed and are hypothesized to direct affect the removal effect. This model also takes account of the potential effect of spatial location (longitude, latitude). Our *a priori* model predicted that environmental conditions (i.e., climate and soil) would have direct effects on the ecosystem responses of woody removal, as well as indirect effects, mediated by the encroachment signature (i.e., initial cover of woody plants and traits of the removed woody plants). The different woody plant removal treatments and time since removal were fixed according to the particular studies, as selection of removal method depends on many financial and feasible factors, and the time of measuring removal effects was decided by the people conducted the study. Therefore, we only explored the direct effects of treatment method and time on ecosystem responses in this meta-analysis.

Supplementary Table 1. Response variables arranged by ecological attributes for ecosystem structure, function and composition and the cases number for each variable at either encroachment or removal database. Our study conducted analysis on the LnRR of 'Overall' and 'Ecological attributes' (except for 'Other') categories.

Overall	Ecological attributes	Response variables	Removal	Encroach
Ecosystem composition	Animal diversity	Amphibian abundance	32	0
Ecosystem composition	Animal diversity	Amphibian diversity	4	1
Ecosystem composition	Animal diversity	Arthropod abundance	157	66
Ecosystem composition	Animal diversity	Arthropod diversity	114	18
Ecosystem composition	Animal diversity	Bird abundance	149	0
Ecosystem composition	Animal diversity	Bird diversity	29	9
Ecosystem composition	Animal diversity	Mammal abundance	179	1
Ecosystem composition	Animal diversity	Mammal diversity	108	27
Ecosystem composition	Microbial diversity	Bacterial abundance	3	73
Ecosystem composition	Microbial diversity	Bacterial diversity	1	10
Ecosystem composition	Microbial diversity	Fungal abundance	16	40
Ecosystem composition	Microbial diversity	Fungal richness	40	2
Ecosystem composition	Microbial diversity	Microbial abundance	0	8
Ecosystem composition	Plant diversity	Forb richness	39	0
Ecosystem composition	Plant diversity	Graminoids richness	17	0
Ecosystem composition	Plant diversity	Grass richness	212	1
Ecosystem composition	Plant diversity	Herb richness	79	0
Ecosystem composition	Plant diversity	Herbaceous richness	119	0
Ecosystem composition	Plant diversity	Plant richness	484	132
Ecosystem composition	Plant diversity	Shrub richness	135	17
Ecosystem composition	Plant diversity	Tree richness	56	4
Ecosystem composition	Plant diversity	Woody richness	24	1
Ecosystem function	Carbon stocks	Aboveground C	40	19
Ecosystem function	Carbon stocks	Belowground plant C	16	9
Ecosystem function	Carbon stocks	Soil C	196	530
Ecosystem function	Non-woody biomass	Forb biomass	193	12
Ecosystem function	Non-woody biomass	Graminoids biomass	16	0
Ecosystem function	Non-woody biomass	Grass biomass	630	10
Ecosystem function	Non-woody biomass	Herb biomass	14	0
Ecosystem function	Non-woody biomass	Herbaceous biomass	28	0
Ecosystem function	Soil fertility	Soil enzyme	48	1
Ecosystem function	Soil fertility	Soil nutrients	309	707
Ecosystem function	Soil hydrology	Soil infiltration	38	56
Ecosystem function	Soil hydrology	Soil moisture	139	70
Ecosystem function	Soil stability	Leaching nutrition	22	0
Ecosystem function	Soil stability	Runoff	62	18
Ecosystem function	Soil stability	Soil sediment	49	3

Ecosystem function	Soil stability	Soil stability	12	45
Ecosystem function	Woody biomass	Shrub biomass	188	8
Ecosystem function	Woody biomass	Tree biomass	29	0
Ecosystem function	Woody biomass	Woody biomass	13	1
Ecosystem function	Other	Belowground biomass	0	1
Ecosystem function	Other	Cryptogam biomass	6	0
Ecosystem function	Other	Environment condition	4	0
Ecosystem function	Other	Evapotranspiration	50	53
Ecosystem function	Other	Forage biomass	158	0
Ecosystem function	Other	Litter biomass	76	10
Ecosystem function	Other	Litter decomposition	1	7
Ecosystem function	Other	Microbial biomass	9	5
Ecosystem function	Other	Microbial nutrient	0	12
Ecosystem function	Other	Plant nutrition	286	54
Ecosystem function	Other	Plant physiology	59	3
Ecosystem function	Other	Pollination	0	3
Ecosystem function	Other	Soil element	35	38
Ecosystem function	Other	Soil microtopography	50	0
Ecosystem function	Other	Soil physical properties	130	321
Ecosystem function	Other	Vegetation biomass	186	120
Ecosystem function	Other	Water recharge	13	5
Ecosystem function	Other	Species turnover	34	0
Ecosystem function	Other	Landscape proportion	8	0
Ecosystem function	Other	Plant interactions	6	2
Ecosystem function	Other	Animal biomass	10	2
Ecosystem structure	Litter cover	Litter cover	143	14
Ecosystem structure	Non-woody cover	Fern cover	12	0
Ecosystem structure	Non-woody cover	Forb cover	266	2
Ecosystem structure	Non-woody cover	Graminoids cover	37	0
Ecosystem structure	Non-woody cover	Grass cover	542	48
Ecosystem structure	Non-woody cover	Herb cover	54	0
Ecosystem structure	Non-woody cover	Herbaceous cover	36	1
Ecosystem structure	Non-woody cover	Legumes cover	2	0
Ecosystem structure	Non-woody density	Forb density	182	0
Ecosystem structure	Non-woody density	Grass density	294	0
Ecosystem structure	Non-woody density	Herb density	1	0
Ecosystem structure	Woody cover	Shrub cover	576	62
Ecosystem structure	Woody cover	Tree cover	132	7
Ecosystem structure	Woody cover	Woody cover	135	1
Ecosystem structure	Woody density	Shrub density	267	5
Ecosystem structure	Woody density	Tree density	98	0
Ecosystem structure	Woody density	Woody density	59	1
Ecosystem structure	Bareground cover	Bare ground cover	152	33

Ecosystem structure	Biocrust cover	Cryptogam cover	73	22
Ecosystem structure	Other	Forb structure	6	0
Ecosystem structure	Other	Graminoids structure	8	0
Ecosystem structure	Other	Grass structure	32	6
Ecosystem structure	Other	Lichen density	4	0
Ecosystem structure	Other	Litter structure	10	1
Ecosystem structure	Other	Mean proximity index	3	0
Ecosystem structure	Other	Mean shape index	2	0
Ecosystem structure	Other	Moss density	12	0
Ecosystem structure	Other	Nearest neighbor distance	4	0
Ecosystem structure	Other	Nest height	3	0
Ecosystem structure	Other	Patch density	24	0
Ecosystem structure	Other	Patch size	3	33
Ecosystem structure	Other	Plant density	19	0
Ecosystem structure	Other	Shrub structure	120	7
Ecosystem structure	Other	Tree structure	299	6
Ecosystem structure	Other	Vegetation cover	225	104
Ecosystem structure	Other	Vegetation density	112	6
Ecosystem structure	Other	Vegetation structure	9	18
Ecosystem structure	Other	Woody structure	49	0
Ecosystem structure	Other	Woody survival	121	0

Supplementary Table 2. The database of 9 attributes of the 213 woody plants that were managed in studies. Notes: Height = mean height (m); Shape = the shape of the woody canopy; Ground = whether foliage contact ground, Pala = Palatability, Allelo = Allelopathy, Y = yes, N = no; Deciduous = deciduousness; Root = roots type i.e. L = lateral, T = tap, LT = lateral and tap root.

Genera	Dominant woody species	Height	Ground	Shape	Deciduous	Pala	N fixation	Allelo	Resprout	Root
Abies	*Abies grandis*	55	N	pyramidal	Evergreen	Y	N	Y	Y	LT
Acacia	*Acacia aneura*	1	N	pyramidal	Evergreen	Y	Y	N	Y	LT
Acacia	*Acacia bellula*	3	Y	round	Evergreen	Y	Y	N	Y	T
Acacia	*Acacia caven*	4	N	v-shaped	Deciduous	Y	Y	Y	Y	T
Acacia	*Acacia cyclops*	3	Y	round	Evergreen	Y	Y	N	Y	T
Acacia	*Acacia drepanolobium*	8.8	N	v-shaped	Deciduous	Y	Y	Y	Y	LT
Acacia	*Acacia gilliesii*	3	N	v-shaped	Deciduous	Y	Y	Y	Y	L
Acacia	*Acacia karroo*	7	N	round	Deciduous	N	Y	Y	Y	LT
Acacia	*Acacia mearnsii*	6	Y	round	Evergreen	Y	Y	N	Y	LT
Acacia	*Acacia mellifera*	6.7	N	v-shaped	Deciduous	Y	Y	Y	Y	LT
Acacia	*Acacia mellifera*	7.5	N	v-shaped	Deciduous	Y	Y	Y	Y	LT
Acacia	*Acacia nigrescens*	10	N	v-shaped	Deciduous	N	Y	Y	Y	T
Acacia	*Acacia rigidula*	3	N	v-shaped	Deciduous	Y	Y	Y	Y	T
Acacia	*Acacia saligna*	10	N	round	Evergreen	Y	Y	Y	Y	LT
Acacia	*Acacia tortilis*	12	N	round	Deciduous	Y	Y	Y	Y	LT
Acacia	*Acacia verticillata*	3	N	v-shaped	Evergreen	N	Y	Y	Y	T
Acer	*Acer campestre*	15	N	round	Deciduous	N	N	N	N	T
Acer	*Acer circinatum*	4.5	N	round	Deciduous	Y	N	N	Y	T
Acer	*Acer macrophyllum*	17	N	round	Deciduous	Y	N	N	N	T

Acer	*Acer rubrum*	22	N	round	Deciduous	Y	N	N	N	L
Acer	*Acer saccharum*	30	N	pyramidal	Deciduous	Y	N	N	Y	LT
Adenostoma	*Adenostoma fasciculatum*	2	N	pyramidal	Deciduous	Y	N	N	Y	LT
Alnenion	*Alnenion viridis*	1	Y	round	Deciduous	N	Y	Y	Y	LT
Alnus	*Alnus glutinosa*	30	N	pyramidal	Deciduous	Y	Y	Y	Y	LT
Alnus	*Alnus sibirica*	10	N	pyramidal	Deciduous	N	Y	Y	Y	T
Aloysia	*Aloysia gratissima*	2.5	N	pyramidal	Deciduous	Y	N	N	Y	L
Amorpha	*Amorpha fruticosa*	3	Y	round	Deciduous	Y	N	Y	Y	LT
Arctostaphylos	*Arctostaphylos canescens*	1.5	N	round	Deciduous	Y	N	Y	N	LT
Arctostaphylos	*Arctostaphylos patula*	1.5	Y	round	Deciduous	Y	N	Y	Y	T
Arctostaphylos	*Arctostaphylos uva-ursi*	0.1	Y	round	Evergreen	Y	N	N	Y	L
Arctostaphylos	*Arctostaphylos viscida*	2.5	N	round	Deciduous	Y	N	Y	Y	T
Artemisia	*Artemisia frigida*	0.1	Y	weeping	Deciduous	Y	N	Y	N	LT
Artemisia	*Artemisia monosperma*	0.8	Y	weeping	Evergreen	Y	N	N	N	LT
Artemisia	*Artemisia ordosica*	0.2	Y	round	Deciduous	Y	N	Y	N	LT
Artemisia	*Artemisia rothrockii*	0.35	Y	round	Evergreen	N	N	Y	N	LT
Artemisia	*Artemisia tridentata*	0.8	Y	round	Evergreen	Y	N	Y	N	LT
Asimina	*Asimina triloba*	10	Y	round	Evergreen	N	N	N	N	T
Aspidosperma	*Aspidosperma*	20	N	round	Deciduous	Y	Y	Y	Y	L
Avicennia	*Avicennia germinans*	8	Y	round	Evergreen	N	N	N	Y	LT
Baccharis	*Baccharis conferta*	1.5	Y	round	Deciduous	Y	N	N	N	T
Baccharis	*Baccharis pilularis*	3	Y	weeping	Evergreen	N	N	N	Y	LT
Baccharis	*Baccharis punctulata*	1	Y	round	Evergreen	N	N	Y	Y	L
Bacharis	*Bacharis*	2	Y	weeping	Evergreen	Y	N	Y	Y	L
Berberis	*Berberis vulgaris*	2	Y	round	Deciduous	N	N	N	Y	L

Betula	*Betula fruticosa*	0.5	Y	round	Evergreen	N	N	N	Y	L
Betula	*Betula glandulosa*	1	Y	round	Deciduous	N	N	Y	N	LT
Betula	*Betula nana*	1	Y	round	Deciduous	Y	N	N	N	L
Betula	*Betula sp.*	1	Y	round	Deciduous	Y	N	N	N	L
Brachypodium	*Brachypodium pinnatum*	0.5	Y	pyramidal	Evergreen	Y	N	N	Y	L
Brachystegia	*Brachystegia spiciformis*	8	N	v-shaped	Deciduous	Y	Y	N	Y	LT
Callitris	*Callitris glaucophylla*	0.5	N	pyramidal	Evergreen	N	N	Y	Y	LT
Calluna	*Calluna vulgaris*	0.35	Y	round	Evergreen	Y	N	N	Y	L
Capparis	*Capparis atamisquea*	4	N	v-shaped	Deciduous	Y	N	N	Y	L
Caragana	*Caragana brachypoda*	0.5	Y	round	Deciduous	Y	Y	N	Y	L
Caragana	*Caragana microphylla*	0.8	Y	round	Deciduous	Y	Y	N	Y	L
Cassinia	*Cassinia aculeata*	1.75	N	v-shaped	Evergreen	N	N	N	Y	LT
Ceanothus	*Ceanothus cordulatus*	40	N	pyramidal	Evergreen	Y	N	Y	N	T
Ceanothus	*Ceanothus cuneatus*	2	Y	weeping	Evergreen	Y	N	N	Y	T
Ceanothus	*Ceanothus velutinus*	2	Y	weeping	Evergreen	Y	Y	N	Y	T
Celtis	*Celtis ehrenbergiana*	2	Y	round	Evergreen	Y	N	N	Y	L
Chrysanthemoides	*Chrysanthemoides monilifera*	2	Y	round	Evergreen	N	N	Y	Y	T
Chrysolepis	*Chrysolepis sempervirens*	2.1	N	round	Evergreen	Y	N	N	Y	T
Chuquiraga	*Chuquiraga avellanedae*	0.5	Y	round	Evergreen	N	N	Y	Y	T
Chuquiraga	*Chuquiraga erinacea*	2	Y	round	Evergreen	Y	N	N	Y	T
Cistus	*Cistus ladanifer*	1	Y	round	Deciduous	N	N	Y	Y	T
Cistus	*Cistus monspeliensis*	1	Y	round	Evergreen	N	N	Y	Y	LT
Cistus	*Cistus salvifolius*	0.6	Y	round	Evergreen	N	N	N	Y	L
Combretum	*Combretum apiculatum*	8	N	v-shaped	Deciduous	N	N	N	Y	L
Combretum	*Combretum laxum*	15	N	v-shaped	Evergreen	N	N	N	Y	T

Combretum	*Combretum tenuifolium*	6	N	pyramidal	Deciduous	Y	N	N	Y	L
Condalia	*Condalia microphylla*	1	Y	v-shaped	Evergreen	Y	N	Y	Y	T
Cornus	*Cornus drummondii*	5.5	N	round	Deciduous	Y	N	N	Y	T
Cornus	*Cornus sericea*	2.5	Y	round	Deciduous	Y	N	N	Y	L
Crossopteryx	*Crossopteryx ferrunginea*	7	N	v-shaped	Evergreen	N	N	N	N	T
Curatella	*Curatella americana*	4	N	round	Deciduous	N	N	Y	Y	LT
Cylindropuntia	*Cylindropuntia fulgida*	2	N	v-shaped	Evergreen	Y	N	N	Y	L
Cytisus	*Cytisus scoparius*	2	Y	round	Evergreen	Y	Y	N	Y	T
Detarium	*Detarium microcarpum*	15	N	v-shaped	Deciduous	Y	N	N	Y	T
Dichrostachys	*Dichrostachys cinerea*	1	Y	weeping	Deciduous	Y	Y	N	Y	LT
Diospyros	*Diospyros lycioides*	3	Y	round	Evergreen	N	N	N	Y	LT
Dodonaea	*Dodonaea viscosa*	2	N	v-shaped	Evergreen	Y	N	N	Y	LT
Echinospartum	*Echinospartum horridum*	0.1	Y	round	Evergreen	N	N	N	Y	L
Eremophila	*Eremophila gilesii*	0.3	Y	round	Evergreen	N	N	N	Y	LT
Eremophila	*Eremophila mitchellii*	0.5	Y	v-shaped	Evergreen	N	N	N	Y	T
Eremophila	*Eremophila sturtii*	2.5	Y	v-shaped	Evergreen	N	N	N	Y	T
Erica	*Erica scoparia*	2	Y	v-shaped	Evergreen	N	N	Y	Y	LT
Eucalyptus	*Eucalyptus coolabah*	2	N	round	Evergreen	N	N	N	Y	T
Eucalyptus	*Eucalyptus crebera*	2	N	round	Evergreen	N	N	N	Y	T
Eucalyptus	*Eucalyptus grandis*	30	N	pyramidal	Evergreen	N	N	N	Y	T
Eucalyptus	*Eucalyptus largiflorens*	2	N	round	Evergreen	N	N	N	Y	T
Eucalyptus	*Eucalyptus populnea*	2	N	round	Evergreen	N	N	Y	Y	LT
Flourensia	*Flourensia cernua*	1	N	v-shaped	Deciduous	N	N	N	Y	L
Frangula	*Frangula alnus*	4	Y	round	Deciduous	Y	N	Y	Y	L
Galenia	*Galenia africana*	0.5	Y	v-shaped	Deciduous	N	N	Y	Y	T

Genista	*Genista hirsuta*	0.8	Y	round	Evergreen	N	Y	Y	Y	T
Genista	*Genista scorpius*	1.5	Y	v-shaped	Deciduous	N	Y	N	Y	LT
Gliricidia	*Gliricidia sepium*	10	N	v-shaped	Deciduous	Y	Y	Y	Y	LT
Grewia	*Grewia flava*	0.5	Y	weeping	Deciduous	Y	N	N	N	LT
Guiera	*Guiera senegalensis*	2	Y	v-shaped	Evergreen	Y	Y	Y	Y	T
Gutierrezia	*Gutierrezia sarothrae*	0.6	Y	round	Deciduous	Y	N	N	Y	T
Haloxylon	*Haloxylon ammodendron*	6	Y	v-shaped	Evergreen	N	N	Y	N	LT
ilex	*ilex vomitoria*	6	Y	weeping	Evergreen	Y	N	N	N	L
Isocoma	*Isocoma veneta*	0.4	Y	round	Deciduous	N	N	N	Y	LT
Juniperus	*Juniperus ashei*	10	N	v-shaped	Evergreen	N	N	Y	N	T
Juniperus	*Juniperus communis*	9	N	round	Evergreen	N	N	Y	Y	T
Juniperus	*Juniperus excelsa*	10	Y	round	Evergreen	N	Y	Y	N	T
Juniperus	*Juniperus monosperma*	2	Y	round	Evergreen	N	N	Y	N	LT
Juniperus	*Juniperus nana*	0.2	N	pyramidal	Evergreen	N	N	Y	N	T
Juniperus	*Juniperus occidentalis*	8	N	pyramidal	Evergreen	N	N	Y	N	T
Juniperus	*Juniperus osteosperma*	6	N	pyramidal	Evergreen	N	N	Y	Y	LT
Juniperus	*Juniperus oxycedrus*	1	N	round	Evergreen	N	N	Y	N	T
Juniperus	*Juniperus pinchoti*	8	N	pyramidal	Evergreen	Y	N	Y	N	LT
Juniperus	*Juniperus sabrina*	1.5	Y	weeping	Evergreen	N	N	Y	N	LT
Juniperus	*Juniperus virginiana*	14	N	pyramidal	Evergreen	N	N	Y	N	LT
Larrea	*Larrea cuneifolia*	2	N	v-shaped	Evergreen	Y	N	Y	Y	T
Larrea	*Larrea divaricata*	2	N	v-shaped	Evergreen	Y	N	N	Y	LT
Larrea	*Larrea tridentata*	2	N	v-shaped	Evergreen	N	N	Y	Y	LT
Leucaena	*Leucaena leucocephala*	10	N	v-shaped	Deciduous	Y	Y	Y	Y	L
Ligustrum	*Ligustrum sinense*	5	N	round	Deciduous	Y	Y	Y	Y	T

Liquidambar	*Liquidambar styraciflua*	18	N	round	Deciduous	Y	N	N	Y	L
Lonicera	*Lonicera maackii*	4	N	v-shaped	Deciduous	Y	Y	Y	Y	LT
Lonicera	*Lonicera morrowii*	2	N	round	Deciduous	Y	Y	Y	Y	L
Lupinus	*Lupinus arboreus*	1.5	Y	round	Evergreen	Y	Y	N	N	L
Maerua	*Maerua crassifolia*	1	Y	round	Evergreen	Y	N	N	Y	T
Maireana	*Maireana pyramidata*	1	Y	round	Deciduous	N	N	N	Y	T
Mimosa	*Mimosa biuncifera*	0.5	Y	v-shaped	Deciduous	Y	Y	N	Y	LT
Mulinum	*Mulinum spinosum*	0.5	Y	round	Evergreen	N	N	N	Y	T
Myoporum	*Myoporum montanum*	0.5	Y	round	Evergreen	N	N	Y	Y	T
Myrcia	*Myrcia guianensis*	2	N	round	Evergreen	N	N	Y	N	LT
Myrica	*Myrica cerifera*	3.5	N	round	Evergreen	Y	Y	N	Y	T
Phlomis	*Phlomis fruticosa*	1	Y	round	Evergreen	Y	N	N	Y	T
Picea	*Picea abies*	40	N	pyramidal	Evergreen	Y	N	N	N	LT
Picea	*Picea engelmannii*	30	N	pyramidal	Evergreen	Y	N	N	N	T
Picea	*Picea glauca*	20	N	pyramidal	Evergreen	Y	N	N	N	LT
Picea	*Picea mariana*	10	N	pyramidal	Evergreen	Y	N	N	N	LT
Pinus	*Pinus banksiana*	15	N	pyramidal	Evergreen	Y	N	N	N	T
Pinus	*Pinus elliottii*	22	N	v-shaped	Evergreen	Y	N	N	N	T
Pinus	*Pinus monophylla*	5	Y	v-shaped	Evergreen	N	N	Y	N	T
Pinus	*Pinus palustris*	30	N	v-shaped	Evergreen	Y	N	Y	N	T
Pinus	*Pinus pinea*	17	N	v-shaped	Evergreen	N	N	Y	N	T
Pinus	*Pinus ponderosa*	40	N	pyramidal	Evergreen	N	N	Y	N	T
Pinus	*Pinus resinosa*	25	N	pyramidal	Evergreen	Y	N	Y	N	T
Pinus	*Pinus strobus*	50	N	pyramidal	Deciduous	Y	N	Y	N	T
Pinus	*Pinus sylvestris*	35	N	pyramidal	Evergreen	Y	N	N	N	T

Pinus	*Pinus spp.*	40	N	pyramidal	Evergreen	N	N	Y	N	T
Pistacia	*Pistacia lentiscus*	2.5	N	v-shaped	Evergreen	Y	N	Y	Y	T
Populus	*Populus deltoides*	30	N	v-shaped	Deciduous	Y	Y	Y	Y	L
Populus	*Populus tremuloides*	20	N	pyramidal	Evergreen	Y	N	N	Y	T
Portulacaria	*Portulacaria afra*	1.5	Y	weeping	Evergreen	N	N	N	Y	L
Potentilla	*Potentilla fruticosa*	0.6	Y	round	Deciduous	N	N	Y	Y	LT
Prosopis	*Prosopis affinis*	5	N	v-shaped	Deciduous	Y	Y	Y	Y	T
Prosopis	*Prosopis caldenia*	8	N	weeping	Deciduous	Y	Y	N	N	T
Prosopis	*Prosopis glandulosa*	8	Y	weeping	Deciduous	Y	N	N	Y	LT
Prosopis	*Prosopis juliflora*	5	Y	v-shaped	Deciduous	Y	Y	N	Y	LT
Prosopis	*Prosopis laevigata*	7	Y	weeping	Deciduous	Y	Y	N	Y	LT
Prosopis	*Prosopis velutina*	10	Y	weeping	Deciduous	Y	Y	N	Y	LT
Pruno	*Pruno spinosae-Crataegetum*	0.3	Y	round	Evergreen	N	N	N	Y	L
Prunus	*Prunus spinosa*	3	Y	round	Deciduous	N	N	N	Y	LT
Pseudotsuga	*Pseudotsuga menziesii*	40	N	pyramidal	Evergreen	Y	N	Y	Y	LT
Pteronia	*Pteronia incana*	0.3	Y	round	Evergreen	Y	N	N	Y	LT
Purshia	*Purshia tridentata*	3	Y	round	Deciduous	Y	N	Y	Y	L
Quercus	*Quercus coccifera*	4	Y	weeping	Evergreen	N	N	Y	Y	T
Quercus	*Quercus ellipsoidalis*	1	Y	weeping	Deciduous	N	N	Y	Y	T
Quercus	*Quercus emoryi*	5	Y	weeping	Evergreen	N	N	Y	Y	T
Quercus	*Quercus havardii*	1	N	v-shaped	Deciduous	Y	N	Y	Y	T
Quercus	*Quercus ilex*	1	Y	weeping	Evergreen	Y	N	Y	Y	T
Quercus	*Quercus marilandica*	15	N	round	Deciduous	Y	N	Y	Y	T
Quercus	*Quercus petraea*	30	N	round	Deciduous	Y	N	Y	Y	T
Quercus	*Quercus pyrenaica*	20	N	pyramidal	Deciduous	N	N	Y	Y	LT

Quercus	*Quercus rubra*	18	N	pyramidal	Deciduous	Y	N	Y	Y	T
Quercus	*Quercus stellata*	12	N	pyramidal	Deciduous	Y	N	Y	Y	T
Quercus	*Quercus turbinella*	3	Y	round	Evergreen	Y	N	N	Y	T
Quercus	*Quercus virginiana*	20	N	round	Evergreen	Y	N	Y	Y	T
Retama	*Retama sphaerocarpa*	3	N	v-shaped	Evergreen	N	Y	N	Y	T
Rhamnus	*Rhamnus cathartica*	5	Y	v-shaped	Deciduous	N	N	Y	Y	T
Rhododendron	*Rhododendron ferrugineum*	0.3	Y	round	Evergreen	N	N	Y	Y	L
Rhododendron	*Rhododendron maximum*	4	N	round	Evergreen	N	N	Y	N	T
Rhus	*Rhus aromatic*	3	Y	round	Deciduous	Y	N	N	Y	T
Rhus	*Rhus glabra*	3	Y	round	Deciduous	Y	N	N	Y	T
Ribes	*Ribes missouriense*	2	N	round	Deciduous	Y	N	N	N	LT
Rosa	*Rosa multiflora*	3	Y	round	Evergreen	N	N	N	Y	L
Rosmarinus	*Rosmarinus officinalis*	0.3	Y	round	Evergreen	N	N	Y	Y	L
Rubus	*Rubus parviflorus*	2	Y	weeping	Deciduous	Y	N	Y	Y	L
Rubus	*Rubus ulmifolius*	2	Y	weeping	Deciduous	Y	N	Y	Y	T
Salix	*Salix caroliniana*	8	N	v-shaped	Deciduous	Y	N	N	Y	T
Salix	*Salix cinerea*	6	Y	round	Deciduous	Y	N	Y	Y	LT
Salix	*Salix pulchra*	1.2	Y	round	Deciduous	Y	N	Y	Y	LT
Salix	*Salix repens*	1.75	Y	round	Deciduous	Y	N	N	Y	T
Sarcopoterium	*Sarcopoterium spinosum*	0.5	Y	weeping	Deciduous	N	N	Y	Y	T
Schinus	*Schinus terebinthifolius*	8	N	v-shaped	Evergreen	Y	N	Y	Y	LT
Sclerocarya	*Sclerocarya caffra*	12	N	v-shaped	Evergreen	N	N	N	Y	LT
Searsia	*Searsia erosa*	1.5	Y	round	Evergreen	N	N	N	Y	L
Senna	*Senna artemisioides*	0.5	Y	round	Evergreen	N	Y	N	Y	LT
Serenoa	*Serenoa repens*	2	Y	round	Deciduous	N	N	Y	Y	LT

Shepherdia	*Shepherdia argentea*	1	Y	round	Deciduous	N	Y	N	Y	LT
Sorbaria	*Sorbaria sorbifolia*	1	Y	round	Deciduous	Y	N	Y	Y	LT
Stipa	*Stipa tenacissima*	0.3	Y	weeping	Evergreen	Y	N	N	Y	L
Symphoricarpos	*Symphoricarpos occidentalis*	0.6	Y	round	Deciduous	Y	N	N	Y	L
Tamarisk	*Tamarisk aphylla*	5	N	v-shaped	Deciduous	Y	Y	Y	Y	T
Terminalia	*Terminalia sericea*	9	N	v-shaped	Deciduous	N	N	Y	Y	L
Tetradymia	*Tetradymia canescens*	1	Y	round	Deciduous	Y	N	Y	Y	LT
Tilia	*Tilia americana*	25	N	pyramidal	Deciduous	Y	N	N	Y	T
Ulex	*Ulex europaeus*	3	Y	round	Deciduous	N	Y	Y	Y	T
Vaccinium	*Vaccinium angustifolium*	0.3	Y	weeping	Deciduous	Y	N	N	Y	L
Vaccinium	*Vaccinium corymbosum*	2.5	N	v-shaped	Deciduous	Y	N	N	N	L
Vaccinium	*Vaccinium fragile*	0.5	Y	round	Evergreen	N	N	N	Y	L
Vaccinium	*Vaccinium myrtillus*	1.5	N	v-shaped	Deciduous	N	N	Y	Y	L
Vachellia	*Vachellia constricta*	2	Y	round	Evergreen	Y	Y	N	Y	T
Vachellia	*Vachellia erioloba*	15	N	v-shaped	Deciduous	N	N	N	Y	LT
Vachellia	*Vachellia karroo*	8	Y	round	Evergreen	Y	Y	N	Y	T
Vachellia	*Vachellia tenuispina*	2.5	Y	round	Evergreen	Y	Y	N	Y	T
Vachellia	*Vachellia tortilis*	12	Y	weeping	Evergreen	Y	Y	Y	Y	LT
Viguiera	*Viguiera dentate*	0.3	Y	round	Evergreen	Y	N	N	N	L

Supplementary Table 3. Numerical values ranked categorical woody plant traits.

Shape				Ground contact		Deciduousness	
v-shaped	weeping	round	pyramid	Yes	No	Deciduous	Evergreen
1	2	2	3	2	1	2	1

Allelopathy		Nitrogen fixation		Roots type			Resprout	
Yes	No	Yes	No	T	L	LT	Yes	No
1	2	2	1	1	2	3	2	1

Supplementary Table 4. Test for funnel plot asymmetry. *P* value was extracted based on two-side test

	Ecosystem measure	z	*P* value
Encroachment	Aervage	1.33	0.18
	Ecosystem structure	1.33	0.18
	Ecosystem function	1.15	0.25
	Ecosystem composition	0.52	0.60
Removal	Average	0.09	0.93
	Ecosystem structure	0.39	0.70
	Ecosystem function	-0.79	0.43
	Ecosystem composition	-1.12	0.26

Supplementary Table 5. Egger regression result. *P* value was extracted based on two-side test

	Ecosystem measure	F-statistic	DF	*P* value
Encroachment	Average	5.297	2676	0.02
	Ecosystem structure	2.32	343	0.13
	Ecosystem function	23.30	1855	1.503e-06
	Ecosystem composition	0.26	390	0.61
Removal	Average	0.53	8189	0.47
	Ecosystem structure	399.30	3799	< 2.2e-16
	Ecosystem function	23.38	2499	1.411e-06
	Ecosystem composition	4.14	1793	0.04

Supplementary Table 6. Trim and fill test. *P* value was extracted based on two-side test

	Ecosystem measure	Number of studies	Missing studies	*P* value
Encroachment	Average	2678	0	0.25
	Ecosystem structure	345	0	0.50
	Ecosystem function	1858	1	0.25
	Ecosystem composition	395	3	0.06
Removal	Average	8200	0	0.50
	Ecosystem structure	3801	0	0.50
	Ecosystem function	2509	8	0.002
	Ecosystem composition	1795	0	0.50

Supplementary Table 7. Random forest for examining the relative importance of plant traits on encroachment and removal impact in Figure 3C. %IncMSE is explained variance. Response variable with not enough data to conduct random forest for either encroachment or removal database were not included. *P* value was extracted based on two-side test

	Response variables (LnRR)	Plant traits	%IncMSE	*P* value
Removal	Carbon stocks	Roots	22.72	0.01
Removal	Carbon stocks	Plant height	14.90	0.03
Removal	Carbon stocks	Allelopathy	14.54	0.01
Removal	Carbon stocks	Palatability	14.42	0.01
Removal	Carbon stocks	Deciduousness	13.73	0.11
Removal	Carbon stocks	Ground contact	13.23	0.01
Removal	Carbon stocks	Canopy shape	8.59	0.23
Removal	Carbon stocks	Resprout	7.94	0.18
Removal	Carbon stocks	Nitrogen fixation	6.29	0.11
Removal	Soil stability	Nitrogen fixation	28.92	0.01
Removal	Soil stability	Plant height	25.60	0.03
Removal	Soil stability	Allelopathy	25.01	0.02
Removal	Soil stability	Roots	22.51	0.02
Removal	Soil stability	Resprout	21.44	0.02
Removal	Soil stability	Deciduousness	16.05	0.21
Removal	Soil stability	Canopy shape	14.83	0.26
Removal	Soil stability	Ground contact	14.69	0.35
Removal	Soil stability	Palatability	4.43	0.68
Removal	Soil hydrology	Plant height	32.19	0.01
Removal	Soil hydrology	Nitrogen fixation	22.14	0.21
Removal	Soil hydrology	Allelopathy	20.12	0.22
Removal	Soil hydrology	Roots	15.94	0.51
Removal	Soil hydrology	Deciduousness	11.84	0.07
Removal	Soil hydrology	Palatability	9.54	0.77
Removal	Soil hydrology	Resprout	9.12	0.61
Removal	Soil hydrology	Ground contact	7.13	0.91
Removal	Soil hydrology	Canopy shape	5.91	0.99
Removal	Soil fertility	Plant height	30.97	0.01
Removal	Soil fertility	Palatability	24.47	0.01
Removal	Soil fertility	Roots	24.33	0.01
Removal	Soil fertility	Allelopathy	22.43	0.01
Removal	Soil fertility	Canopy shape	16.69	0.05
Removal	Soil fertility	Deciduousness	14.32	0.02
Removal	Soil fertility	Nitrogen fixation	14.00	0.02
Removal	Soil fertility	Resprout	13.75	0.02
Removal	Soil fertility	Ground contact	11.35	0.03
Removal	Non-woody biomass	Plant height	51.82	0.01

Removal	Non-woody biomass	Allelopathy	39.07	0.01
Removal	Non-woody biomass	Canopy shape	38.84	0.01
Removal	Non-woody biomass	Deciduousness	31.14	0.01
Removal	Non-woody biomass	Roots	30.47	0.01
Removal	Non-woody biomass	Palatability	25.36	0.01
Removal	Non-woody biomass	Resprout	24.23	0.01
Removal	Non-woody biomass	Ground contact	20.87	0.01
Removal	Non-woody biomass	Nitrogen fixation	9.26	0.14
Removal	Plant diversity	Plant height	56.01	0.01
Removal	Plant diversity	Roots	33.23	0.01
Removal	Plant diversity	Palatability	31.96	0.01
Removal	Plant diversity	Deciduousness	31.70	0.01
Removal	Plant diversity	Canopy shape	25.42	0.01
Removal	Plant diversity	Allelopathy	21.80	0.01
Removal	Plant diversity	Nitrogen fixation	21.37	0.01
Removal	Plant diversity	Ground contact	18.38	0.01
Removal	Plant diversity	Resprout	16.58	0.01
Removal	Microbial diversity	Ground contact	13.92	0.01
Removal	Microbial diversity	Plant height	13.78	0.09
Removal	Microbial diversity	Deciduousness	7.44	0.16
Removal	Microbial diversity	Resprout	6.95	0.83
Removal	Microbial diversity	Palatability	6.51	0.22
Removal	Microbial diversity	Allelopathy	6.17	0.76
Removal	Microbial diversity	Roots	5.38	0.25
Removal	Microbial diversity	Canopy shape	5.09	0.74
Removal	Microbial diversity	Nitrogen fixation	4.16	0.76
Removal	Animal diversity	Plant height	41.61	0.01
Removal	Animal diversity	Roots	39.41	0.01
Removal	Animal diversity	Deciduousness	37.42	0.01
Removal	Animal diversity	Canopy shape	33.86	0.01
Removal	Animal diversity	Palatability	31.06	0.01
Removal	Animal diversity	Resprout	27.54	0.01
Removal	Animal diversity	Nitrogen fixation	26.30	0.01
Removal	Animal diversity	Allelopathy	21.31	0.06
Removal	Animal diversity	Ground contact	18.87	0.01
Removal	Litter cover	Plant height	29.59	0.01
Removal	Litter cover	Deciduousness	27.41	0.01
Removal	Litter cover	Roots	21.40	0.01
Removal	Litter cover	Palatability	18.86	0.02
Removal	Litter cover	Allelopathy	18.72	0.02
Removal	Litter cover	Ground contact	14.85	0.04
Removal	Litter cover	Resprout	13.86	0.01
Removal	Litter cover	Canopy shape	13.06	0.32
Removal	Litter cover	Nitrogen fixation	11.90	0.08

Encroachment	Carbon stocks	Plant height	37.76	0.03
Encroachment	Carbon stocks	Ground contact	32.61	0.01
Encroachment	Carbon stocks	Deciduousness	31.19	0.05
Encroachment	Carbon stocks	Resprout	30.26	0.02
Encroachment	Carbon stocks	Roots	28.79	0.03
Encroachment	Carbon stocks	Nitrogen fixation	28.30	0.02
Encroachment	Carbon stocks	Palatability	26.19	0.01
Encroachment	Carbon stocks	Allelopathy	22.87	0.18
Encroachment	Carbon stocks	Canopy shape	21.24	0.28
Encroachment	Soil stability	Canopy shape	23.33	0.01
Encroachment	Soil stability	Plant height	20.26	0.01
Encroachment	Soil stability	Palatability	19.86	0.01
Encroachment	Soil stability	Allelopathy	16.29	0.05
Encroachment	Soil stability	Roots	13.61	0.09
Encroachment	Soil stability	Ground contact	13.17	0.20
Encroachment	Soil stability	Nitrogen fixation	7.31	0.24
Encroachment	Soil stability	Resprout	3.40	0.65
Encroachment	Soil stability	Deciduousness	0.00	0.51
Encroachment	Soil hydrology	Plant height	29.45	0.06
Encroachment	Soil hydrology	Palatability	21.72	0.24
Encroachment	Soil hydrology	Resprout	18.72	0.18
Encroachment	Soil hydrology	Ground contact	17.34	0.21
Encroachment	Soil hydrology	Canopy shape	17.19	0.18
Encroachment	Soil hydrology	Deciduousness	15.69	0.30
Encroachment	Soil hydrology	Allelopathy	14.91	0.28
Encroachment	Soil hydrology	Nitrogen fixation	5.66	0.12
Encroachment	Soil hydrology	Roots	4.44	0.74
Encroachment	Soil fertility	Plant height	28.76	0.01
Encroachment	Soil fertility	Deciduousness	24.89	0.01
Encroachment	Soil fertility	Allelopathy	23.88	0.01
Encroachment	Soil fertility	Roots	23.70	0.01
Encroachment	Soil fertility	Nitrogen fixation	18.73	0.03
Encroachment	Soil fertility	Palatability	17.71	0.01
Encroachment	Soil fertility	Ground contact	14.89	0.01
Encroachment	Soil fertility	Resprout	14.70	0.05
Encroachment	Soil fertility	Canopy shape	14.46	0.05
Encroachment	Non-woody biomass	Allelopathy	19.65	0.01
Encroachment	Non-woody biomass	Plant height	15.83	0.05
Encroachment	Non-woody biomass	Nitrogen fixation	14.64	0.02
Encroachment	Non-woody biomass	Palatability	9.07	0.35
Encroachment	Non-woody biomass	Roots	8.90	0.50
Encroachment	Non-woody biomass	Canopy shape	8.82	0.44
Encroachment	Non-woody biomass	Deciduousness	7.45	0.68
Encroachment	Non-woody biomass	Ground contact	0.00	1.00

Encroachment	Non-woody biomass	Resprout	0.00	1.00
Encroachment	Plant diversity	Plant height	31.65	0.01
Encroachment	Plant diversity	Deciduousness	20.22	0.24
Encroachment	Plant diversity	Roots	19.64	0.27
Encroachment	Plant diversity	Canopy shape	19.37	0.02
Encroachment	Plant diversity	Nitrogen fixation	16.11	0.50
Encroachment	Plant diversity	Palatability	13.89	0.38
Encroachment	Plant diversity	Allelopathy	13.72	0.20
Encroachment	Plant diversity	Ground contact	12.58	0.49
Encroachment	Plant diversity	Resprout	3.09	0.13
Encroachment	Microbial diversity	Plant height	17.93	0.02
Encroachment	Microbial diversity	Nitrogen fixation	13.23	0.01
Encroachment	Microbial diversity	Roots	11.99	0.01
Encroachment	Microbial diversity	Ground contact	10.73	0.01
Encroachment	Microbial diversity	Canopy shape	10.03	0.25
Encroachment	Microbial diversity	Deciduousness	0.00	1.00
Encroachment	Microbial diversity	Palatability	0.00	1.00
Encroachment	Microbial diversity	Allelopathy	0.00	1.00
Encroachment	Microbial diversity	Resprout	0.00	1.00
Encroachment	Animal diversity	Canopy shape	14.72	0.79
Encroachment	Animal diversity	Resprout	13.88	0.59
Encroachment	Animal diversity	Ground contact	12.88	0.94
Encroachment	Animal diversity	Plant height	12.19	0.82
Encroachment	Animal diversity	Allelopathy	10.66	1.00
Encroachment	Animal diversity	Deciduousness	9.91	0.97
Encroachment	Animal diversity	Roots	9.49	0.97
Encroachment	Animal diversity	Nitrogen fixation	9.23	0.93
Encroachment	Animal diversity	Palatability	8.88	0.96
Encroachment	Litter cover	Allelopathy	13.60	0.06
Encroachment	Litter cover	Roots	13.10	0.02
Encroachment	Litter cover	Ground contact	8.66	0.36
Encroachment	Litter cover	Canopy shape	6.77	0.28
Encroachment	Litter cover	Plant height	4.52	0.76
Encroachment	Litter cover	Nitrogen fixation	2.11	0.92
Encroachment	Litter cover	Palatability	1.33	0.78
Encroachment	Litter cover	Deciduousness	0.71	0.76
Encroachment	Litter cover	Resprout	0.00	1.00

Supplementary Table 8. Model comparison between Model 1 (linear): LnRR ~ x and Model 2 (polynomial): LnRR ~ poly (x, 2). Difference is the Model 1 minus AIC of Model 2 and value are bold if ≤ 2 (20 out of 35) which indicate Model 1 is better, otherwise Model 2 is selected to fit the data. Response variable without sufficient data (less than 60) did not fit regression model. *P* value was extracted based on two-side test.

Response variable	Independent variable	AIC_linear	AIC_poly	Difference	N
Animal diversity	Woody cover	403.43	397.55	5.88	176
Bareground cover	Woody cover	178.03	150.87	27.16	98
Biocrust cover	Woody cover	35.98	37.94	**-1.97**	33
Carbon stocks	Woody cover	179.27	165.23	14.04	147
Litter cover	Woody cover	108.99	110.93	**-1.94**	88
Non-woody biomass	Woody cover	1495.88	1496.51	**-0.64**	547
Non-woody cover	Woody cover	1562.79	1563.32	**-0.53**	603
Non-woody density	Woody cover	809.85	809.99	**-0.14**	284
Plant diversity	Woody cover	458.60	456.75	**1.85**	309
Soil fertility	Woody cover	198.18	195.31	2.87	123
Woody biomass	Woody cover	431.14	429.39	**1.74**	136
Woody cover	Woody cover	1359.04	1357.78	**1.26**	421
Woody density	Woody cover	391.07	392.73	**-1.66**	131
Composition	Woody cover	1011.00	1013.00	**-2.00**	525
Function	Woody cover	4009.00	3956.00	53.00	1515
Structure	Woody cover	5913.00	5912.00	**1.00**	1928
Animal diversity	Time	1940.56	1928.35	12.21	759
Bareground cover	Time	390.38	383.86	6.52	149
Biocrust cover	Time	154.99	155.02	**-0.03**	70
Carbon stocks	Time	297.14	294.50	2.64	252
Litter cover	Time	275.20	276.93	**-1.73**	141
Non-woody biomass	Time	2553.09	2555.09	**-2.00**	871
Non-woody cover	Time	2206.11	2195.63	10.48	890
Non-woody density	Time	1350.50	1350.71	**-0.21**	477
Plant diversity	Time	1705.11	1705.02	**0.09**	1154
Soil fertility	Time	670.92	670.85	**0.07**	357
Soil hydrology	Time	402.63	404.61	**-1.98**	174
Soil stability	Time	394.89	388.56	6.33	145
Woody biomass	Time	797.18	791.28	5.90	230
Woody cover	Time	2737.55	2739.49	**-1.94**	826
Woody density	Time	1352.75	1349.06	3.68	420
Composition	Time	4110.00	4102.00	8.00	1973
Function	Time	8868.00	8864.00	4.00	3132
Structure	Time	12185.00	12187.00	**-2.00**	4034

Supplementary Table 9. Summary of linear and polynomial regression between ecosystem response to removal (ecosystem structure, function and composition, and ecological attributes) and initial woody cover or time since removal [$\log_e(x+1)$ transformed]. Model structure for each response variable was determined by AIC difference in Table S7 (≤2, linear structure, >2 polynomial structure). Coefficient is the estimate, SE is standardized error, t value and significance P value, poly (…) 1 and poly (…) 2 indicate polynomial 1 (first order) and 2 (second order), respectively. Significance is based on P <0.05 (two-side test). Ecological attributes with insufficient data (≤ 60) were not included to fit regression.

Response variable (LnRR)	term	Coefficient	SE	t value	P value
Biocrust cover	Woody cover	0.00	0.01	0.69	0.50
Litter cover	Woody cover	0.00	0.00	-0.95	0.34
Non-woody biomass	Woody cover	0.00	0.00	0.47	0.64
Non-woody cover	Woody cover	0.00	0.00	-1.34	0.18
Non-woody density	Woody cover	-0.01	0.01	-1.12	0.27
Plant diversity	Woody cover	0.00	0.00	-0.21	0.83
Woody biomass	Woody cover	0.01	0.01	0.98	0.33
Woody cover	Woody cover	0.00	0.00	0.64	0.52
Woody density	Woody cover	0.01	0.00	2.44	0.02
Composition	Woody cover	0.00	0.00	-1.48	0.14
Structure	Woody cover	0.00	0.00	-1.16	0.25
Animal diversity	poly(woody_cover, 2, raw = TRUE)1	0.02	0.01	2.50	0.01
Animal diversity	poly(woody_cover, 2, raw = TRUE)2	0.00	0.00	-2.82	0.01
Bareground cover	poly(woody_cover, 2, raw = TRUE)1	0.05	0.01	4.29	0.00
Bareground cover	poly(woody_cover, 2, raw = TRUE)2	0.00	0.00	-5.74	0.00
Carbon stocks	poly(woody_cover, 2, raw = TRUE)1	0.02	0.01	3.25	0.00
Carbon stocks	poly(woody_cover, 2, raw = TRUE)2	0.00	0.00	-4.07	0.00
Soil fertility	poly(woody_cover, 2, raw = TRUE)1	0.01	0.01	1.18	0.24
Soil fertility	poly(woody_cover, 2, raw = TRUE)2	0.00	0.00	-2.20	0.03
Function	poly(woody_cover, 2, raw = TRUE)1	0.02	0.00	6.57	0.00
Function	poly(woody_cover, 2, raw = TRUE)2	0.00	0.00	-7.47	0.00
Biocrust cover	Time	-0.28	0.13	-2.13	0.04
Litter cover	Time	0.03	0.08	0.45	0.65
Non-woody biomass	Time	-0.07	0.06	-1.18	0.24
Non-woody density	Time	0.09	0.07	1.22	0.22
Plant diversity	Time	-0.02	0.02	-0.69	0.49
Soil fertility	Time	0.04	0.03	1.16	0.25
Soil hydrology	Time	0.12	0.08	1.49	0.14
Woody cover	Time	0.26	0.07	3.92	0.00
Structure	Time	0.06	0.02	2.51	0.01
Animal diversity	poly(log_time, 2, raw = TRUE)1	0.81	0.17	4.70	0.00
Animal diversity	poly(log_time, 2, raw = TRUE)2	-0.18	0.05	-3.78	0.00

Bareground cover	poly(log_time, 2, raw = TRUE)1	-1.46	0.45	-3.26	0.00
Bareground cover	poly(log_time, 2, raw = TRUE)2	0.38	0.13	2.93	0.00
Carbon stocks	poly(log_time, 2, raw = TRUE)1	0.37	0.13	2.77	0.01
Carbon stocks	poly(log_time, 2, raw = TRUE)2	-0.08	0.04	-2.15	0.03
Non-woody cover	poly(log_time, 2, raw = TRUE)1	0.65	0.17	3.74	0.00
Non-woody cover	poly(log_time, 2, raw = TRUE)2	-0.18	0.05	-3.54	0.00
Soil stability	poly(log_time, 2, raw = TRUE)1	1.58	0.68	2.34	0.02
Soil stability	poly(log_time, 2, raw = TRUE)2	-0.46	0.16	-2.90	0.00
Woody biomass	poly(log_time, 2, raw = TRUE)1	-1.90	0.67	-2.86	0.00
Woody biomass	poly(log_time, 2, raw = TRUE)2	0.61	0.22	2.82	0.01
Woody density	poly(log_time, 2, raw = TRUE)1	0.61	0.28	2.15	0.03
Woody density	poly(log_time, 2, raw = TRUE)2	-0.18	0.07	-2.38	0.02
Composition	poly(log_time, 2, raw = TRUE)1	0.31	0.08	3.79	0.00
Composition	poly(log_time, 2, raw = TRUE)2	-0.07	0.02	-3.17	0.00
Function	poly(log_time, 2, raw = TRUE)1	-0.25	0.09	-2.76	0.01
Function	poly(log_time, 2, raw = TRUE)2	0.06	0.03	2.33	0.02

Supplementary Table 10. Random forest for selecting plant traits to include in SEM for explaining removal impact. Random Forest analysis was conducted on the whole removal database that contained available data for all predictors (particularly encroachment stages, removal time) included in the Structural Equation Modelling. %IncMSE is explained variance. Drivers were ranked by their explained variance and elected attributes were bold in text. *P* value was extracted based on two-side test.

Plant traits	%IncMSE	P value
Plant height	34.538	0.010
Canopy shape	26.759	0.010
Deciduousness	25.715	0.010
Resprout	22.791	0.010
Root type	21.475	0.010
Palatability	19.875	0.010
Nitrogen fixation	17.458	0.020
Allelopathy	14.021	0.010
Ground contact	13.903	0.010

Appendix S1. Detailed background information on the procedure for selecting relevant studies

We carefully examined every paper that was suitable for including in our quantitative analysis to ensure that the meta-analysis database was comprehensive and objective. Papers were only included in our database if they met the following *a priori criteria*: (i) the study was conducted under natural field conditions (greenhouse or growth chamber studies, as well as studies using cultivated plants, were not considered), (ii) the results were quantitative and therefore analysable, and (iii) the variables were collected strictly in plots encroached and without woody vegetation for the woody plant encroachment studies or in plot with woody plant removed and woody plant retained for the woody plant removal studies located in the same geographical area (hereafter encroached and removed plots as treatment, plots without woody plant and woody retained plots as control). This allowed us to be certain that any effects observed at each study could be attributed to the effects of encroachment or removal, and not to variation in climatic or soil type between the treatment and control plots. (iv) studies were included when the impacts resulted only from woody plant encroachment/invasion or woody plant removal rather than the invasion or removal of other plant species. In some studies, many exotic plant species rather than only woody species was invaded in the ecosystem or all the understorey vegetation was removed instead of only removing woody plants, so these studies were excluded; (v) studies were included only if the reported data were representative of whole grassland and encroached plots for encroachment studies and were representative of land that dominated by woody plants and removed plots. Studies that evaluated the effects of woody vegetation or without woody plant on the response variables considered at the microsite level (e.g. comparing the effects of shrub vs. grass canopies on vegetation or soil attributes within the same site) were not considered.

For woody plant removal database, studies with shared controls (multiple treatments with one control) were included only if these treatments were conducted in the same

geographical area and during the same period. Studies comparing before and after treatment with no specific control treatment were not regarded as paired and were therefore excluded from the database. For example, for woody plant encroachment database, most, but not all, of these data represented encroachment scenarios. A small number represented naturally-occurring areas of dense shrubland (e.g. the Succulent Karoo in Southern Africa; Todd & Hoffman 1999) and these were compared with shrub-free, generally grass-dominant sites. While not all of these grassland–shrubland plots were strictly cross-fence comparisons i.e. they did not always occur immediately adjacent to each other, they were always within a few kilometers away, and therefore represented two different ends of the woody encroachment–grassland continuum. Many of the studies reported results from only a single encroached-grassland plot at the same site and therefore lacked measurement errors.

Appendix S2. List of literature for compiling the woody plant encroachment and woody plant removal database

List of 216 papers for compiling the woody plant encroachment database.

1. Abrahams, A.D., Parsons A.J. & Wainwright J. (1994). Resistance to overland flow on semiarid grassland and shrubland hillslopes, Walnut Gulch, southern Arizona. *J. Hydrol.*, 156, 431-446.
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3. Angassa, A. & Baars R.M.T. (2000). Ecological condition of encroached and non-encroached rangelands in Borana, Ethiopia. *Afr. J. Ecol.*, 38, 321-328.
4. Angassa, A. (2002). The effect of clearing bushes and shrubs on range condition in Borana, Ethiopia. *Trop. Grassl.*, 36, 69-76.
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13. Barbosa da Silva, F. H., Arieira, J., Parolin, P., Cátia Nunes da, C., & Junk, W. J. (2016). Shrub encroachment influences herbaceous communities in flooded

grasslands of a neotropical savanna wetland. *Applied Vegetation Science, 19*(3), 391-400. doi: http://dx.doi.org/10.1111/avsc.12230

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19. Benshahar, R. (1992). The effects of bush clearance of African ungulates in a semiarid nature reserve. *Ecol. Appl.*, 2, 95-101.

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Appendix S3. Converting categorical woody plant traits to numeric value

We converted the categorical traits into numeric values by ranking each categorical trait such that a larger number represented greater function in terms of its own growth or for facilitating surrounding conditions. For plant shape, we ranked different shapes according to a greater ability to obtain resources for the understorey (water and light) with v-shaped plants accumulate resources for itself while pyramid plants accumulate more rainfall for understorey (De Soyza et al., 1997). For ground contact (i.e. whether foliage contact ground), high values were ranked according to the ability to provide habitat for understorey species with ground contact plant can better protect understorey habitat (Wang et al., 2013; Okin et al., 2006). For deciduousness, we ranked the higher value for the ability of such species to benefit their growth conditions (e.g., greater litter inputs to the soil nutrient pool) (Van Breemen et al., 1995). For allelopathy, we ranked a higher value based on the probability to facilitate surrounding species (i.e. non-allelopathy plants) (Gómez-Aparicio & Canham, 2008). For nitrogen fixation, we ranked the higher value for nitrogen fixed plants for its ability to help its growth and maintenance (McKinley & Blair, 2008). For roots type, higher values were ranked by ability to increase nutrition cycling with lateral roots are better in accelerating soil nutrient cycling (Attiwill & Adams, 1993). For resprout, we ranked the higher value for its ability to resprout to sustain the woody plant habitat (Heisler et al., 2004). The numerical value ranked for each categorical trait and the range of trait value was shown in Supplementary Table 3 and Supplementary Fig. 3.

Appendix S4. Publication bias examination

First, we used funnel plot to visually show the relationship between effect size residuals and study precision (1/SE) (Supplementary Fig. 4). The funnel plots were based on a mixed-effect model estimating mean effect sizes of the dataset for each response variable. The funnel plots indicate that for ecosystem structure, function and composition dataset for either encroachment database or removal database, there is no visually publication bias. In addition, test for funnel plot asymmetry for the average, ecosystem structure, function and composition for the two databases are all insignificant ($P > 0.05$), which accept the null hypothesis and means that these funnel plots are symmetry (Supplementary Table 4). Second, we tested the funnel asymmetry with modified Egger regression suggested by Nakagawa and Santos (2012) to examine the relationship between residual effect size and study precision (1/SE) (Supplementary Table 5). Egger regression showed that (i) for the ecosystem structure and composition dataset of encroachment database, and the average dataset of removal database, there is no publication bias ($P > 0.05$), while (ii) for the rest dataset in the two databases, there may exist publication bias ($P < 0.05$). Third, we further used trim and fill test that searches for asymmetry in funnel plots and imputes 'missing' effect sizes to make the funnel plot symmetrical (Duval & Tweedie 2000) (Supplementary Table 6). For all the encroachment dataset, and the average, ecosystem structure and composition of removal dataset, the test accepts the null hypothesis (there is no missing data at the right/left side) with *P* value above 0.05.

Overall, the result of funnel plot, Egger regression and trim and fill test showed that there is no publication bias in encroachment database, but there might be potential publication bias in the ecosystem function of the removal database. This indicates that caution needed to be taken when interpreting the impact of removal on ecosystem function.

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