

Target-based site prioritization under climate change using quadratic network flow

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1 Introduction

Currently, el 14.9% of terrestrial area is a part of the global protected area network (UNEP-WCMC 2018). However, most of this areas have not been created using prioritization tools developed to maximize species or ecosystems conservation based on current biodiversity patterns (Rodrigues et al. 2004; Jenkins et al. 2015). The situation is even worst when we take into account that the range of species will change over time (Araújo et al. 2004; Chen et al. 2011; Lenoir et al. 2008; Regos et al. 2016), were several species that are now being protected by these areas might not be protected in the future beause of the climate crisis (Alagador, Cerdeira, and Araújo 2014; Araújo et al. 2004).

Despite the concern about protected area planning, in a review Jones et al. (2016) shows that more than 90% of the prioritization planing studies that try to incorporate climate change, only take two time steps into account, current climate and the last step of climate. In order for the species to move from areas were they are currently protected to the future protected areas, their route has to be protected aswell, that is the biological corridors that they will use (Nuñez et al. 2013; Rosenberg, Noon, and Meslow 1997). Thus the planification and creation of those biological corridors correspond to adaptative measures to environmental changes that would mitigate the impacts of the climate crisis (Hannah et al. 2007). In that context, biological corridors besides taking unto account the effects of climate change, they have to take into account changes in land use and habitat fragmentation in order to evaluate the factibility of the species reaching future available habitat.

There have been several different approaches to try to model biological corridors. There has been approaches using close to 3,000 species over all of the aAmericas (Lawler et al. 2013), but those models did not take the species dispersal speed into account or use them to build priority areas. On a more local level, there are several studies that focus in one or a few species (Alagador, Cerdeira, and Araújo 2014; Cushman et al. 2013; Gregory et al. 2014) which is not enough for planning. There are a few examples that take into account group of species, but in very confined spaces (Beier, Majka, and Bayless 2007; Phillips et al. 2008; Williams et al. 2005). Among this articles, the work of Phillips et al. (2008), incorporates the use of the Network Flow optimization method (Ahuja, Magnanti, and Orlin 1993) in order to solve the problem expressed by Williams et al. (2005), generating a solution 33% more efficient than previous optimization methods, this makes this methodology one of the most promising ways of solving conservation planning problems.

In its traditional use Network flow, gives the best possible solution given constrains (Phillips et al. 2008). If we looked at the solution for a species in a raster, every cell would have a value of either one or zero, where one would be a cell necessary for the conservation of the species or a zero if it is not necessary. This best solution, however, only represents one of the possible solutions to conserve a species, and does not give us any alternatives. Quadratic Cost Network Flow as implemented in this research gives us alternative solution, where for every species we would still get a value of one if the cell is irrepleacable for the solution, zero if that cell is not needed, and an intermediate value for cells that are one of many alternative solutions for a given species, this is, for every cell we have an irreplaceability index. Spatial planning is a complex endeavour where agendas, and/or needs evolve rapidly and several alternative subopitmal solutions might be needed in order to navigate this complex desicions.

In this article we present a new method of working with network flow on conservation planning using quadratic costs, while at the same time comparing its results and implications with traditional network flow and zonation using the Northern Tropical Andes ecoregion as an example.

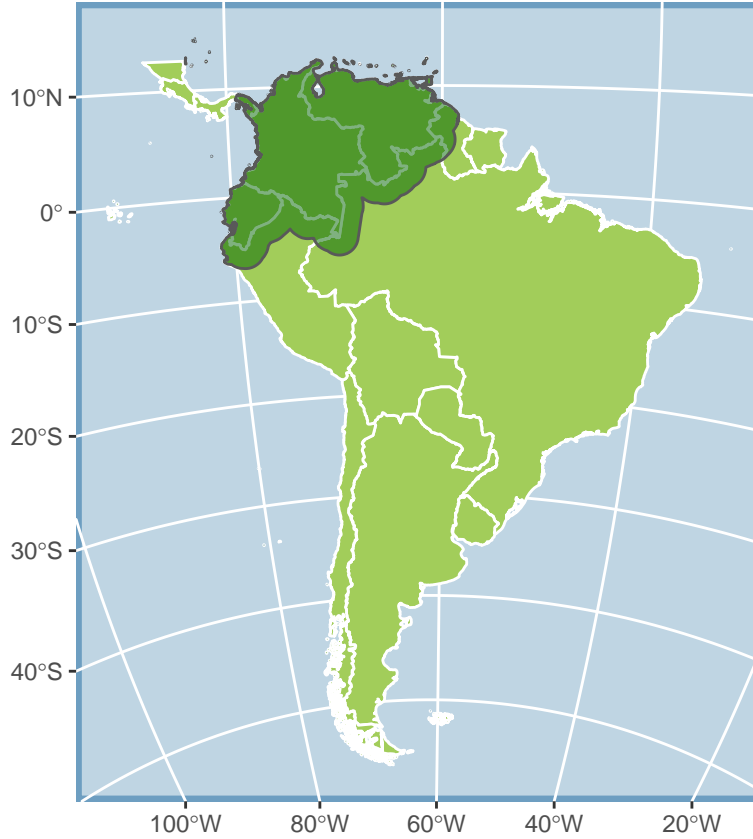


Figure 1: Map of Southamerica, the darkened area is the area where the prioritization was performed

2 Methods

2.1 Area

The studied area was the Northern Tropical Andes, consisting of the countries of Colombia, Venezuela and Ecuador, with a buffer of 200 kilometers around land areas.

The studied area is shown in figure 1 and it encompasses 3,632,762 square kilometers

2.2 Species

671 species of plants were used for the model, only endemic species were used in this study. A list can be found in the supplementary materials

2.3 GCMs

Four GCM models were selected to project the species distribution using the GCMcompareR shiny app (Fajardo et al. 2018), we followed the storylines approach (Zappa and Shepherd 2017) and selected a GCM warmer and wetter, warmer and dryer, colder and wetter, and colder and dryer than the ensemble. The selected models where cc, cn, la, mp al the process is shonw in in figure 2.

2.4 Niche modeling

For each species the species distribution model was fit using the dismo package (Hijmans et al. 2017), using 50,000 random background points and the maxent algorithm (Phillips, Anderson, and Schapire 2006; Merow,

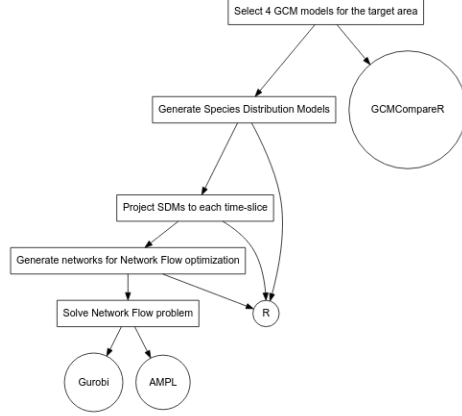


Figure 2: All the steps and programs used in the Optimization

Smith, and Silander Jr 2013)

2.5 Model Description

This model was developed based on the notion of non-overlapping dispersal chains (Williams et al. 2005), and instead of having a binary solution (to protect or not protect an area), the result will be an index of importance going from zero to one. Here, zero means that there are no chains passing by that spacial point that go from the source to the final destination, and one is a point where chains have to pass through to reach the desired flow. In order to do this, we follow Network-flow methods (Ahuja, Magnanti, and Orlin 1993) to model the survival and dispersion of species along the space and time, using species distribution models and quadratic flow costs to split the flow evenly across alternative paths. Therefore, the resulting flow across an arc is high only if there are few alternatives to use that edge to achieve the target flow. Even when model takes into account protected areas (cost zero) and human habitat such as cities (cost infinite) in the decision making, both were not included in this exercise to simplify the examples. This is a generalist model which only needs the distribution model of the species projected to each time slice and the maximum dispersal distance for each species.

2.5.1 Model Formulation

The objective is to minimize the cost

minimize
 $Quadcost$

$$Quadcost = \sum_{i=1}^n (Cost \times Flow_t)^2$$

subject to

$$\text{Initial Flow} = \sum_{i=1}^n Flow_{t_1} = \text{Target paths}$$

$$\text{Final Flow} = \sum_{i=1}^n Flow_{t_{final}} = \text{Target paths}$$

$$\text{Flow capacity} = \sum_{i=1}^n Flow_{(i,t)} \leq capacity_{(i,t)}$$

2.6 Network generation

In order to generate the networks the QuadCostAmpl package was used (Corcoran and Fajardo 2019)

2.7 Linear Network Flow

Model

2.8 Quadratic Network Flow

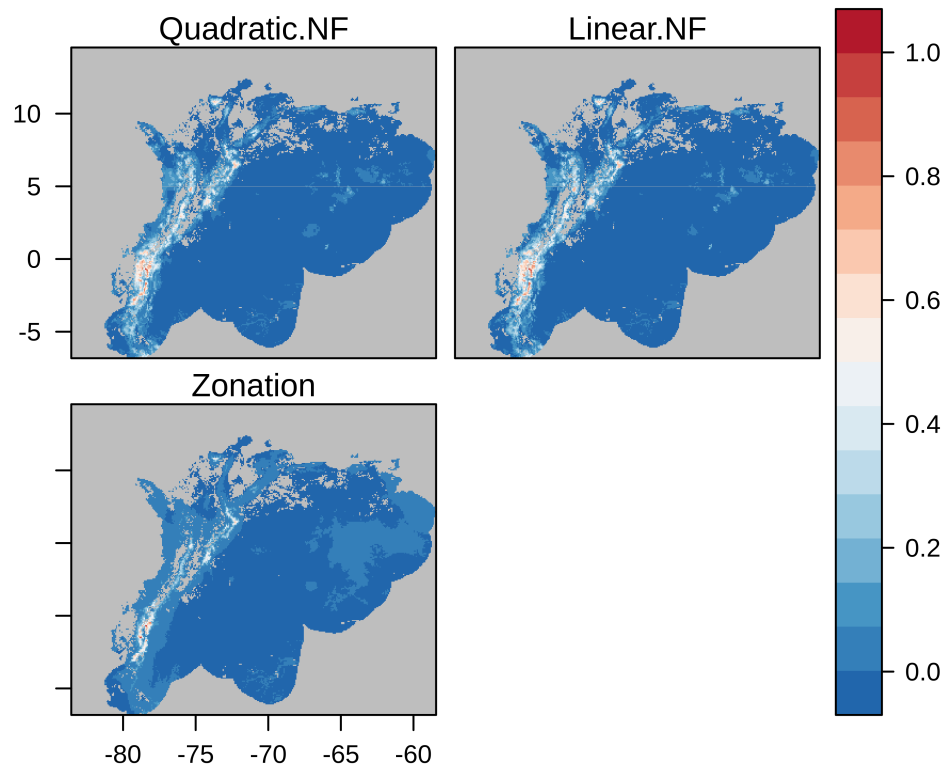
2.9 Zonation

In the examples above, (a) uses the Present Simple tense to describe what is normally done or to describe a standard piece of equipment used in the research and (b) uses the Past Simple tense to describe what you did yourself.

Another difficulty arises with the passive when you write about the procedure you used and compare it with the work of other researchers. You can use the Past Simple agentless passive to describe the procedure you used (the samples were collected using a suction tube) but you may also need to use exactly the same Past Simple agentless passive to describe the procedure used by the other researcher whose work you are citing (the samples were collected using a suction tube).

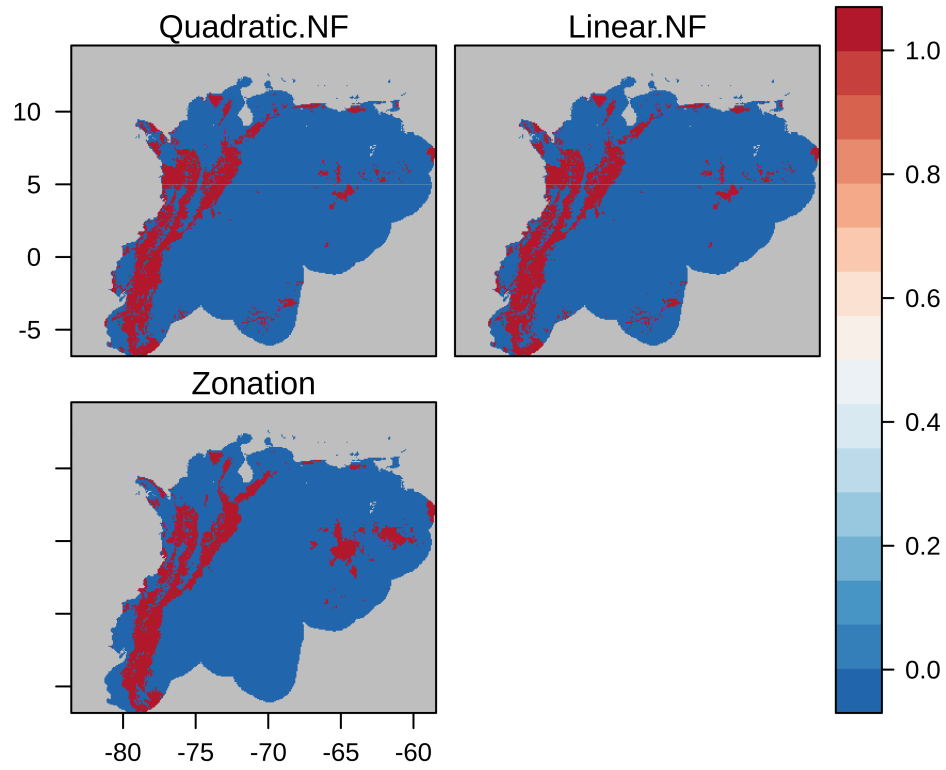
*One way to make sure that your own contribution is clear and easy to identify is by marking it with words — perhaps by adding phrases like **In this study**, the samples were collected using a suction tube or **In our experiments** the samples were collected using a suction tube, and by identifying the procedure used by other researchers with careful references at the appropriate place in the sentence*

Results

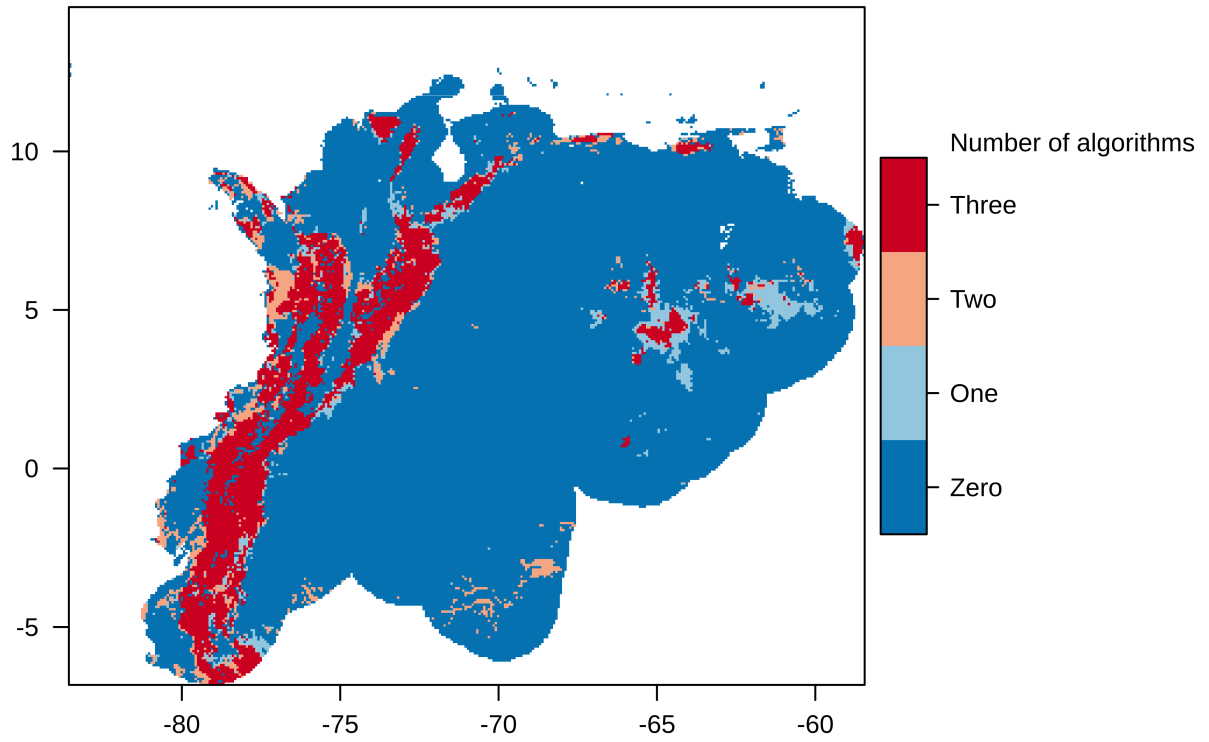


The results of all three algorithms is shown in figure ??

2.9.1 Efficiency comparison (Number of cells)

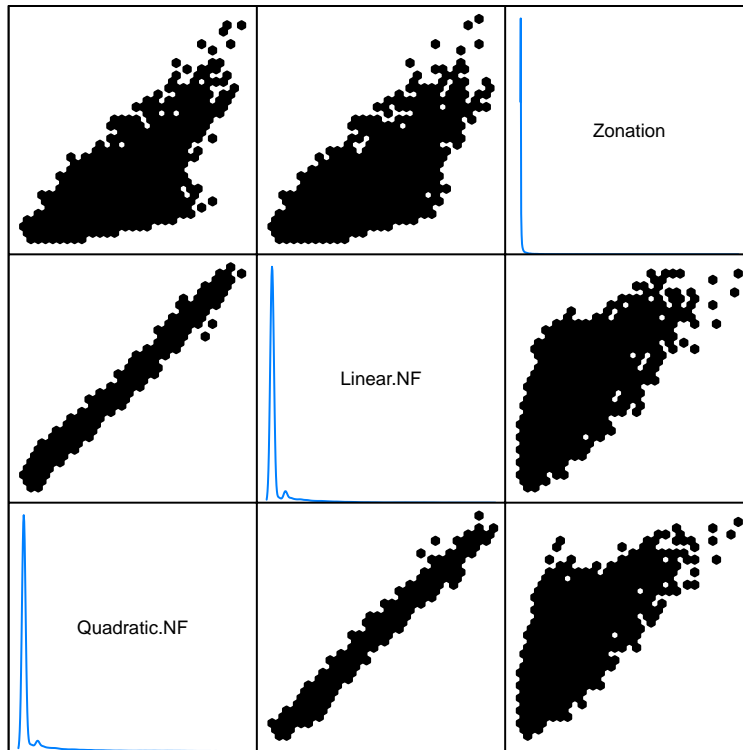


In this example when we calculate the top 10% of protected cells for Quadratic Network Flow we get 482,440 Squared Kms, 480,630 Squared Kms for linear Network Flow, and 482,477 Squared Kms for Zonation. That is 13.2803, 13.2304, 13.2813 percent of the total area respectively.

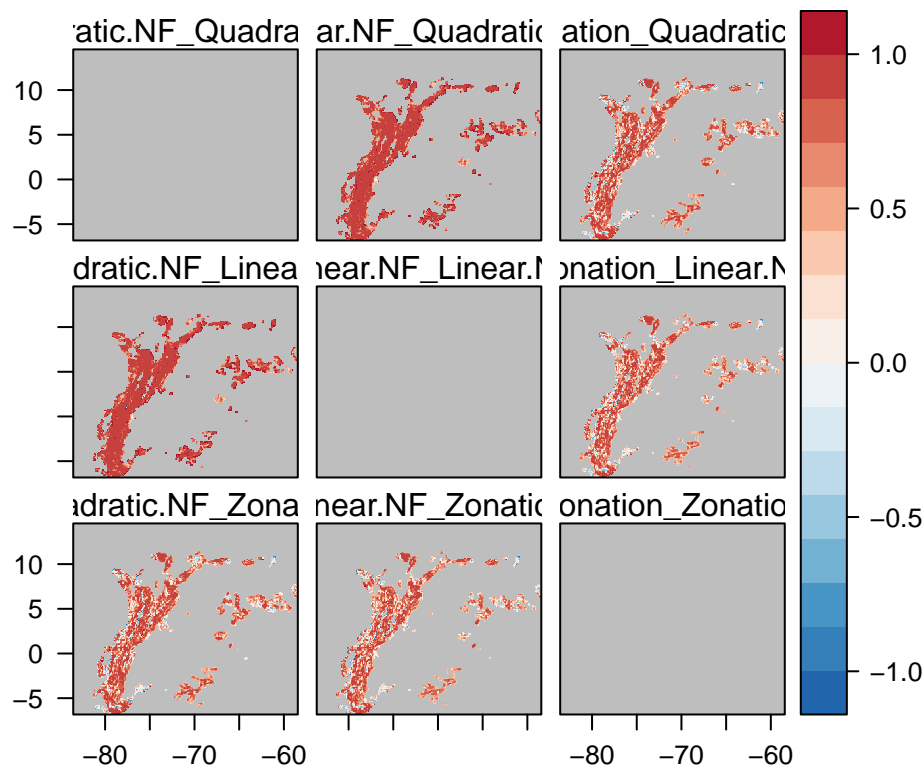


2.9.2 Correlation comparison (Spearman)

rowname	Linear.NF	Quadratic.NF	Zonation
Linear.NF	NA	0.9211996	0.6241322
Quadratic.NF	0.9211996	NA	0.6690281
Zonation	0.6241322	0.6690281	NA



Scatter Plot Matrix



Subsection 2

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3 Discussion

Disclosure/Conflict-of-Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

The statement about the authors and contributors can be up to several sentences long, describing the tasks of individual authors referred to by their initials and should be included at the end of the manuscript before the References section.

Acknowledgments

Funding:

4 Supplemental Data

Supplementary Material should be uploaded separately on submission, if there are Supplementary Figures, please include the caption in the same file as the figure. LaTeX Supplementary Material templates can be found in the Frontiers LaTeX folder

5 References

Figures

6 Supplementary materials

6.1 List of species

The species used for the solution were the following:

Aa maderoi, *Abutilon ibarense*, *Achyrocline crassiceps*, *Aciachne flagellifera*, *Aechmea drakeana*, *Aegiphila pennellii*, *Aequatorium sinuatifolium*, *Aequatorium verrucosum*, *Aetheolaena involucrata*, *Aetheolaena linguata*, *Ageratina asclepiadea*, *Ageratina dendroides*, *Ageratina gynoxoides*, *Ageratina pseudochilca*, *Ageratina theaeifolia*, *Ageratina vacciniaefolia*, *Agouticarpa grandistipula*, *Agrostis boyacensis*, *Agrostis foliata*, *Agrostis trichodes*, *Aiphanes grandis*, *Altensteinia virescens*, *Amazilia castaneiventris*, *Anagallis foemina*, *Anastrophylum nigrescens*, *Andigena laminirostris*, *Anomobryum prostratum*, *Anotomys leander*, *Anredera brachystachys*, *Anthopteris schultzeae*, *Anthurium aristatum*, *Anthurium carchiense*, *Anthurium cordiforme*, *Anthurium flavolineatum*, *Anthurium giganteum*, *Anthurium gualeanum*, *Anthurium herthae*, *Anthurium lancea*, *Anthurium membranaceum*, *Anthurium morae*, *Anthurium palenquense*, *Anthurium pallatangense*, *Anthurium pedunculare*, *Anthurium pendulispadix*, *Anthurium phyllobaris*, *Anthurium rimbachii*, *Anthurium rugulosum*, *Anthurium wattii*, *Aphanactis jamesoniana*, *Aphanactis ollgaardii*, *Aphanactis piloselloides*, *Aragoa abietina*, *Aragoa cundinamarcensis*, *Aragoa occidentalis*, *Arcytophyllum aristatum*, *Arenaria venezuelana*, *Aristeguietia glutinosa*, *Arracacia moschata*, *Arremon phaeopleurus*, *Astragalus geminiflorus*, *Astragalus sprucei*, *Atlapetes flaviceps*, *Atlapetes leucopis*, *Atractus crassicaudatus*, *Atractus lasallei*, *Axinaea merianiae*, *Axinaea sodiroi*, *Azorella aretioides*, *Azorella cuatrecasasii*, *Azorella pedunculata*, *Baccharis revoluta*, *Baccharis rupicola*, *Baccharis teindalensis*, *Badilloa salicina*, *Bangsia aureocincta*, *Bangsia edwardsi*, *Bangsia rothschildi*, *Bartsia laticrenata*, *Bartsia orthocarpiflora*, *Bartsia santolinifolia*, *Bartsia stricta*, *Bauhinia stenantha*, *Begonia tiliifolia*, *Belloa radians*, *Berberis goudotii*, *Berberis hallii*, *Berberis rigidifolia*, *Berberis verticillata*, *Besleria angustiflora*, *Blakea glandulosa*, *Blakea hispida*, *Blakea oldemanii*, *Blakea rotundifolia*, *Bolborhynchus ferrugineifrons*, *Bomarea glaucescens*, *Bomarea linifolia*, *Bomarea patacensis*, *Bomarea uncifolia*, *Bractia andina*, *Brachyotum alpinum*, *Brachyotum confertum*, *Brachyotum fictum*, *Brachyotum gleasonii*, *Brachyotum harlingii*, *Brachyotum jamesonii*, *Brachyotum strigosum*, *Brayopsis colombiana*, *Breutelia squarrosa*, *Breutelia trianae*, *Browneopsis disepala*, *Brugmansia aurea*, *Brunellia boqueronensis*, *Brunellia colombiana*, *Bucquetia glutinosa*, *Buddleja pichinchensis*, *Burmeistera montipomum*, *Calamagrostis aurea*, *Calamagrostis effusa*, *Calamagrostis fibrovaginata*, *Calamagrostis guamanensis*, *Calamagrostis mollis*, *Calamagrostis podophora*, *Calceolaria dilatata*, *Calceolaria ferruginea*, *Calceolaria hyssopifolia*, *Calceolaria lamiifolia*, *Calceolaria pedunculata*, *Calceolaria purpurascens*, *Calceolaria rosmarinifolia*, *Calliargonella cuspidata*, *Campylopus argyrocaulon*, *Campylopus cleefii*, *Campylopus cucullatifolius*, *Campylopus edithae*, *Campylopus incertus*, *Campylopus pittieri*, *Campylopus subconcolor*, *Carex amicta*, *Casearia mexiae*, *Castilleja nubigena*, *Castratella piloselloides*, *Centradeniastrum album*, *Centropogon aequatorialis*, *Centropogon baezanus*, *Centropogon glabrifilis*, *Centropogon medusa*, *Centropogon nigricans*, *Centropogon subandinus*, *Cerastium floccosum*, *Ceratostema alatum*, *Cestrum peruvianum*, *Chalcostigma heteropogon*, *Chorisodontium speciosum*, *Chromolaena bullata*, *Chusquea subulata*, *Cinclodes excelsior*, *Cistothorus apolinari*, *Cistothorus meridae*, *Citharexylum*

sulcatum, *Clavijsa eggersiana*, *Clethra crispa*, *Clinopodium nubigenum*, *Clinopodium taxifolium*, *Clinopodium tomentosum*, *Clusia callejasii*, *Coespeletia moritziana*, *Coespeletia spicata*, *Coespeletia thyrsiformis*, *Coespeletia timotensis*, *Colignonia pentoptera*, *Columnnea albiflora*, *Columnnea capillosa*, *Columnnea ciliata*, *Columnnea eubractea*, *Conirostrum rufum*, *Conyza cardaminifolia*, *Conyza trihecatactis*, *Coursetia gracilis*, *Coussarea pilosiflora*, *Cranichis antioquiensis*, *Cranioleuca hellmayri*, *Critoniopsis occidentalis*, *Critoniopsis palaciosii*, *Critoniopsis sodiroi*, *Cronquistianthus niveus*, *Croton elegans*, *Croton rimbachii*, *Cryptotis equatoris*, *Culcitium nivale*, *Cyanolyca pulchra*, *Cynanchum microphyllum*, *Dalea humifusa*, *Dasyphyllum popayanense*, *Dendrophorbium lloense*, *Diglossa gloriosa*, *Diglossa gloriosissima*, *Diglossa indigotica*, *Diplostephium alveolatum*, *Diplostephium bicolor*, *Diplostephium cayambense*, *Diplostephium cinerascens*, *Diplostephium ericoides*, *Diplostephium frontinense*, *Diplostephium glandulosum*, *Diplostephium hartwegii*, *Diplostephium ochraceum*, *Diplostephium phyllicoides*, *Diplostephium revolutum*, *Diplostephium rhododendroides*, *Diplostephium rhomboidale*, *Diplostephium rupestre*, *Diplostephium schultzii*, *Diplostephium spinulosum*, *Diplostephium tenuifolium*, *Diplostephium tolimense*, *Diplostephium violaceum*, *Diplostichum longirostre*, *Distichia acicularis*, *Ditrichum submersum*, *Draba aretioides*, *Draba hallii*, *Draba obovata*, *Draba splendens*, *Draba spruceana*, *Dracula sodiroi*, *Drepanocladus exannulatus*, *Drymonia crenatiloba*, *Drymonia laciniosa*, *Dysithamnus occidentalis*, *Elaphoglossum antisanae*, *Elaphoglossum heliconiifolium*, *Elaphoglossum yatesii*, *Elasis hirsuta*, *Elatine ecuadoriensis*, *Elleanthus gastroglossis*, *Elleanthus petrogeiton*, *Epidendrum englerianum*, *Epidendrum marsupiale*, *Epidendrum pallatangae*, 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dependens*, *Fuchsia hartwegii*, *Fuchsia macrostigma*, *Fuchsia orientalis*, *Fuchsia sessilifolia*, *Fuchsia sylvatica*, *Fuchsia vulcanica*, *Gasteranthus columbianus*, *Gasteranthus lateralis*, *Gasteranthus leopardus*, *Gasteranthus quitensis*, *Gaultheria cordifolia*, *Geissanthus argutus*, *Genista monspessulana*, *Gentianella cerastioides*, *Gentianella cernua*, *Gentianella corymbosa*, *Gentianella foliosa*, *Gentianella hirculus*, *Gentianella hyssopifolia*, *Gentianella nummulariifolia*, *Gentianella rapunculoides*, *Gentianella rupicola*, *Geonoma divisa*, *Geranium maniculatum*, *Geranium multiceps*, *Geranium multipartitum*, *Glaucidium nubicola*, *Gongylolepis jauaensis*, *Grallaria alleni*, *Grallaria flavotincta*, *Grallaria milleri*, *Grallaria rufocinerea*, *Grallarica lineifrons*, *Grallarica loricata*, *Grosvenoria hypargyra*, *Grosvenoria rimbachii*, *Gustavia longifuniculata*, *Gustavia serrata*, *Guzmania jaramilloi*, *Guzmania lehmanniana*, *Guzmania vanvolxemii*, *Guzmania wittmackii*, *Gynoxys acostae*, *Gynoxys hirsuta*, *Gynoxys laurata*, *Gynoxys miniphylla*, *Gynoxys parvifolia*, *Gynoxys pendula*, *Gynoxys sodiroi*, *Gynoxys stuebelii*, *Gynoxys tolimensis*, *Halenia adpressa*, *Halenia gentianoides*, *Halenia pulchella*, *Haplophaedia lugens*, *Hebeclinium tetragonum*, *Hedyosmum parvifolium*, *Heliangelus strophianus*, *Heliconia dielsiana*, *Heppiella verticillata*, *Hesperomeles goudotiana*, *Hieracium avilae*, *Huperzia capellae*, *Huperzia cruenta*, *Huperzia cumingii*, *Huperzia hystrix*, *Huperzia lindenii*, *Huperzia llanganatensis*, *Huperzia polydactyla*, *Huperzia rufescens*, *Huperzia transilla*, *Huperzia unguiculata*, *Hypericum decandrum*, *Hypericum goyanesii*, *Hypericum myricariifolium*, *Hypericum prostratum*, *Hypericum quitense*, *Hypochaeris setosa*, *Inga extra-nodis*, *Isoetes andina*, *Isoetes bischlerae*, *Isoetes boyacensis*, *Isoetes novo-granadensis*, *Isoetes palmeri*, *Jamesonia bogotensis*, 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courea sodiroi, *Palicourea subalatoidea*, *Pappobolus imbaburensis*, *Paspalum hirtum*, *Passiflora adulterina*,
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grans, *Pentacalia guadalupe*, *Pentacalia ledifolia*, *Pentacalia nitida*, *Pentacalia pulchella*, *Pentacalia reissiana*,
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miqueliana, *Pernettya hirta*, *Phalcooboenus carunculatus*, *Philodendron oligospermum*, *Philodendron rugosum*,
Philonotis andina, *Pilea gallowayana*, *Pinguicula elongata*, *Piper laguna-cochanum*, *Piper sodiroi*, *Piper*
subflavum, *Pipreola jucunda*, *Pitcairnia commixta*, *Pitcairnia cosangaensis*, *Pitcairnia fusca*, *Pittosporum*
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segregatum, *Polytrichadelphus ciliatus*, *Pouteria capacifolia*, *Prunus antioquiensis*, *Prunus herthae*, *Psammisia*
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densinervia, *Rhodostemonodaphne laxa*, *Rhynchospora paramora*, *Ribes hirtum*, *Ribes lehmannii*, *Rubus*
choachiensis, *Rubus gachetensis*, *Ruilopezia atropurpurea*, *Ruilopezia marcescens*, *Rumex tolimensis*, *Saguinus*
leucopus, *Salvia pichinchensis*, *Saurauia chilantha*, *Saurauia crassiseptala*, *Saurauia omichlophila*, *Saurauia*
peduncularis, *Saurauia pseudostrigillosa*, *Schefflera acaropunctata*, *Schefflera lasiogyne*, *Schefflera marginata*,
Schefflera ramosissima, *Scorpidium scorpioides*, *Scytalopus griseicollis*, *Scytalopus rodriguezi*, *Scytalopus*
vicinior, *Senecio culcitoides*, *Senecio formosoides*, *Senecio hypsobates*, *Senecio leucanthemoides*, *Senecio*
madagascariensis, *Senecio niveo-aureus*, *Senecio subbrunneatus*, *Setaria cernua*, *Siparuna croatii*, *Siparuna*
palenquensis, *Siphocampylus affinis*, *Siphocampylus brevicalyx*, *Siphocampylus columnae*, *Solanum crinitipes*,
Solanum paucijugum, *Sorocea sarcocarpa*, *Sparrmannia africana*, *Sphaeradenia hamata*, *Sphaeradenia hor-*
rida, *Sphagnum compactum*, *Sphagnum oxyphyllum*, *Spherospermum boekei*, *Spherospermum grandifolium*,
Sporobolus bogotensis, *Stachys bogotensis*, *Stachys elliptica*, *Stelis columnaris*, *Stelis piperina*, *Stellaria recur-*
vata, *Stenospermation longifolium*, *Stilpnophyllum grandifolium*, *Stilpnophyllum oellgaardii*, *Stipa milleana*,
Stipa rosea, *Symphyogyna bogotensis*, *Symplocos cundinamarcanensis*, *Symplocos rhomboidea*, *Symplocos*
theiformis, *Synallaxis castanea*, *Synallaxis subpudica*, *Syntrichia andicola*, *Tagetes zypaquirensis*, *Tangara*
rufigenis, *Telipogon nervosus*, *Ternstroemia cleistogama*, *Terpsichore heteromorpha*, *Terpsichore pichinchae*,
Tetragastris varians, *Thelypteris rigescens*, *Themistoclesia epiphytica*, *Theobroma gileri*, *Thibaudia andrei*,
Thibaudia grantii, *Thibaudia parvifolia*, *Thomasomys hylophilus*, *Thomasomys niveipes*, *Thryophilus nicefori*,
Tibouchina gleasoniana, *Tibouchina paleacea*, *Tibouchina pendula*, *Tillandsia emergens*, *Tillandsia incarnata*,
Tillandsia lajensis, *Tillandsia secunda*, *Tillandsia superba*, *Tillandsia truncata*, *Tournefortia ramosissima*,
Uncinia paludosa, *Uniola condensata*, *Urothraupis stolzmanni*, *Urtica longispica*, *Valeriana adscendens*,
Valeriana arborea, *Valeriana bracteata*, *Valeriana tatamana*, *Valeriana tomentosa*, *Verbesina brachypoda*,
Verbesina latisquama, *Verbesina lloensis*, *Verbesina sodiroi*, *Viburnum anabaptista*, *Viburnum antioquiense*,
Vigna venusta, *Viola glandularis*, *Vireo masteri*, *Weinmannia polyphylla*, *Wettinia anomala*, *Xenophyllum*
crassum, *Zanthoxylum lepidopteriphilum*, *Zygodon pichinchensis*

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