Changing Ecological Opportunities Facilitated the Explosive Diversification of New Caledonian *Oxera* (Lamiaceae).

Laure Barrabé¹,², Sébastien Lavergne³, Giliane Karnadi-Abdelkader¹, Bryan Drew⁴, Philippe Birnbaum¹,⁵, Gildas Gâteblé¹

¹Institut Agronomique néo-Calédonien (IAC), Equipe ARBOREAL, BP 711, 98810 Mont-Dore, New Caledonia
²Endemia, Plant Red List Authority, 7 rue Pierre Artigue, 98800 Nouméa, New Caledonia
³Laboratoire d’Ecologie Alpine, CNRS - Université Grenoble Alpes, UMR 5553, F-38000 Grenoble, France
⁴Department of Biology, University of Nebraska-Kearney, Kearney, NE 68849, USA
⁵UMR AMAP, Université de Montpellier, CIRAD, CNRS, INRA, IRD, 34398 Montpellier, France

*Correspondence to be sent to: Institut Agronomique néo-Calédonien (IAC), Equipe ARBOREAL, BP 711, 98810 Mont-Dore, New Caledonia, Tel: 687 260809, Fax: 687 437016. E-mail: gateble@iac.nc
ABSTRACT

Phylogenies recurrently demonstrate that oceanic island systems have been home to rapid clade diversification and adaptive radiations. The existence of adaptive radiations posits a central role of natural selection causing ecological divergence and speciation, and some plant radiations have been highlighted as paradigmatic examples of such radiations. However, neutral processes may also drive speciation during clade radiations, with ecological divergence occurring following speciation. Here we document an exceptionally rapid and unique radiation of Lamiaceae within the New Caledonian biodiversity hotspot. Specifically, we investigated various biological, ecological and geographical drivers of species diversification within the genus Oxera. We found that Oxera underwent an initial process of rapid cladogenesis likely triggered by a dramatic period of aridity during the early Pliocene. This early diversification of Oxera was associated with an important phase of ecological diversification triggered by significant shifts of pollination syndromes, dispersal modes, and life forms. Finally, recent diversification of Oxera appears to have been further driven by the interplay of allopatry and habitat shifts likely related to climatic oscillations. This suggests that Oxera could be regarded as an adaptive radiation at an early evolutionary stage that has been obscured by more recent joint habitat diversification and neutral geographical processes. Diversification within Oxera has perhaps been triggered by varied ecological and biological drivers acting in a leapfrog pattern, but geographic processes may have been an equally important driver. We suspect that strictly adaptive radiations may be rare in plants and that most events of rapid clade diversification may have involved a mixture of geographical and ecological divergence.

Keywords: Adaptive radiation, Allopatry, Niche shifts, Leapfrog radiation, Lamiaceae, New Caledonia, Oxera.
Oceanic islands are widely regarded as laboratories of evolution mainly owing to their isolated past biogeographical history (Losos and Ricklefs 2009). Their geographical isolation limits dispersal events from outside, resulting in ecological niches being filled by species diversification rather than colonization. Consequently, islands are expected to have sheltered many adaptive radiations, where single lineages have diversified rapidly into several distinct niches, resulting in disproportionately high phenotypic diversity (Schluter 2000) as compared to their continental relatives (Silvertown et al. 2005). This phenomenon can be particularly apparent on large and high-elevation islands that exhibit diverse and sharp environmental gradients (Whittaker et al. 2008). Although adaptive radiations may not necessarily result from an acceleration of speciation rates (see Givnish 2015 for a discussion), all adaptive radiations are spurred by ecological opportunities; that is, the release of vacant niches due to unused resources, species extinctions or the acquisition of new traits (Losos 2010). The existence of adaptive radiations thus posits a central role of natural selection causing ecological divergence and speciation, and some plant radiations have been highlighted repeatedly as paradigmatic examples of this scenario, such as the silversword alliance and lobeliads in Hawaii (Carlquist et al. 2003; Givnish et al. 2009), the Macaronesian *Aeonium* and *Echium* (Jorgensen and Olesen 2001), and *Veronica* (*Hebe*) in New Zealand (Wagstaff et al. 1998).

However, adaptive radiations *sensu stricto* appear to be quite uncommon in the plant kingdom, with the aforementioned well documented cases probably representing rare exceptions. In fact, many radiations likely occur, at least in part, in a non-adaptive way (Givnish 1997, Rundell and Price 2009). Under such a scenario, speciation is not primarily driven by ecological divergence, but mainly by neutral divergence in allopatry. Ecological differentiation may occur following non-ecological speciation, through random trait divergence, adaptation to different
climatic regimes or habitats, or due to trait divergence favoring local coexistence if secondary sympatry occurs (e.g. Tobias et al. 2014). While molecular phylogenies will often provide little power to discriminate between different scenarios, it remains possible to assess the relative importance of ecological differentiation and geographic divergence in rapid species diversifications. Considering that theoretical evidence suggests that most rapid evolutionary radiations may have occurred through a mixture of ecological speciation and neutral divergence in allopatry (Aguilée et al. 2011, 2012), we can legitimately wonder whether purely adaptive radiations have ever occurred in plants.

The New Caledonian biodiversity hotspot is a remote archipelago in the southwest Pacific, composed of an old, large, and high-elevation main island (= Grande Terre, ca. 37 Ma, ca. 16,600 km², 1600m max. elevation) exhibiting exceptional levels of species richness and endemism (ca. 3400 species, 75% endemic; Morat et al. 2012; Munzinger et al. 2016). The singular geological and climatic New Caledonian history led to the implementation of complex and abrupt environmental gradients, resulting in a mosaic of highly distinct habitats. The archipelago topography is especially complex on Grande Terre, with many relatively steep valleys and high summits (Bonvallot 2012) presenting both physical barriers to dispersal and strong selection gradients. The archipelago also has a suite of diverse bedrock types, in particular volcano-sedimentary, metamorphic and ultramafic (metal-rich soils with chemical and physical properties that constrain plant growth). These latter bedrock types, which act as strong environmental filters and exhibit a patchy distribution, have probably played a key role in plant speciation and flora evolution (Pillon et al. 2010). In addition, Pliocene and Pleistocene climatic fluctuations considerably affected the dynamic of New Caledonian biotas, leading to the origination of new habitats such as the unique shrubby sclerophyllous vegetation (i.e. maquis; Jaffré 1980), during periods of forest contraction (Hope and Pask 1998; Stevenson 2004;
Stevenson and Hope 2005). This likely triggered speciation in palms (Pintaud et al. 2001), and has contributed to the persistence of old angiosperm lineages in forest refugia (Pouteau et al. 2015). All the aforementioned characteristics have contributed to the tremendous plant diversity of New Caledonia (Jaffré 1993), and have also driven numerous plant radiations (e.g., *Psychotria*; *Pycandra*; Munzinger et al. 2016). Though plant radiations are increasingly highlighted in the archipelago through molecular investigations, few studies have focused on the relative effect of drivers implied in their *in situ* diversification (e.g. Barrabé et al. 2014; Pillon et al. 2014; Paun et al. 2016).

The old age, geographic isolation, and geologic and topographic complexity of New Caledonia suggests that adaptive radiations may be common among many genera endemic to New Caledonia. However, few of these genera exhibit the joint signatures of morphological and ecological divergence expected from adaptive radiations, and rather seem to be relictual lineages (Pillon et al. 2017). The woody genus *Diospyros* (Ebenaceae) was the first purported clear case of an adaptive radiation of a plant group within New Caledonia due to its wide ecological diversity (Paun et al. 2016), although the radiation was not related to obvious morphological and/or physiological differences. The tree genus *Geissois* (Cunoniaceae) was described as a cryptic adaptive radiation, in which species exhibit notable differences in leaf element composition likely linked to the occupation of varied soils (Pillon et al. 2014), but does not fully satisfy the criteria of an adaptive radiation as outlined by Givnish (2015), as no physiological adaptation has yet been highlighted. It thus seems that New Caledonia has harbored few, if any, adaptive radiations in a strict sense (sensu Givnish 2015 and Schluter 2000). This has been explained as a consequence of the relatively old age of the island, the prevalence of woody species, the paucity of potential pollinator species, and/or a reduced number of ecological opportunities as compared to other island systems (Pillon et al. 2017).
In this work, we report on a molecular systematic investigation of the genus *Oxera* (Lamiaceae), which has been hypothesized to have diversified in New Caledonia through adaptive radiation (Pillon et al. 2014). The genus is composed of 33 species endemic to New Caledonia (Gâteblé unpublished data, available at http://endemia.nc/flore/fiche588), and was recently enlarged to include five other Australasian and Pacific species (Barrabé et al. 2015). It was demonstrated that the entire New Caledonian clade originated from a single colonization and constitutes the tenth largest plant radiation in the archipelago, which is puzzling given that Lamiaceae are an under-represented family within the flora of New Caledonia (Pillon et al. 2010). Distinct subclades were partially circumscribed within *Oxera* and can arguably be considered as several independent micro-radiations within the genus (Barrabé et al. 2015). *Oxera* exhibits strongly divergent morphology in terms of life form, flowers and fruits, and occupies a vast diversity of distinct habitats. In relation to this remarkable morphological diversity we hypothesize that shifts of functional, reproductive (pollination and dispersal), and environmental niches may have played a key role during the diversification of *Oxera*. This role can be two-fold: (i) niche shifts may have triggered species differentiation and speciation, and (ii) certain niche types may have accelerated the rate of genetic divergence and speciation.

The dazzling morphological and ecological diversity of New Caledonian *Oxera* could reflect adaptations to different ecological factors (see Givnish 2010 for a discussion of life form adaptations). First, the great array of life forms observed in *Oxera* could be associated with different environment preferences, as observed in the silversword alliance (Carlquist et al. 2003), and this may have created conditions that facilitated parapatric isolation and speciation. Robust lianas mainly grow in closed rainforests with leaves usually reaching the canopy, while slender lianas are mostly encountered in open sclerophyllous vegetation and forest edges; monocaulous trees (i.e. single-stemmed) are mainly confined to rainforest understories; and finally, shrub
species are often able to establish in both closed and more open vegetation (Gâteblé, pers. obs.; see Fig. 1a, b). Such contrasting life forms clearly reflect functional strategies regarding growth under different light conditions (Givnish 1995; Santiago and Wright 2007; Selaya and Anten 2008).

Second, most species of Oxera are confined to narrow environmental conditions within New Caledonia. They occur either in rainforests, dry forests or maquis, or occur at different elevations and/or on different bedrock types (limestone, ultramafic, volcano-sedimentary rocks). Although some species of Oxera are clearly specialized towards particular habitats or have very limited geographic ranges in narrow valleys or on remote summits, others are encountered throughout the archipelago due to wider environmental tolerances. These contrasting habitat and geographic patterns may be hypothesized as the signature of parapatric or allopatric speciation processes, and provide an interesting basis for testing whether habitat or geography (or both) have been major drivers of clade diversification.

Third, the floral diversity of Oxera was previously linked to distinct flower pollinators (de Kok 1998) based upon field observations of animal visits (Table 1). These pollinator preferences could potentially be drivers of evolution of reproductive isolation within Oxera. Honey-eaters (Meliphagidae) and white-eyes (Zosteropidae) have been observed visiting Oxera species displaying showy and curved flowers, profusely producing nectar, and bearing arched anthers typically extending out of the corolla (Table 1). Long-tubular white and/or green bilabiate flowers, sometimes releasing a strong fragrance, have been observed to be visited by butterflies and moths (Pieridae and Sphingidae; Table 1; de Kok, 1997; Haxaire and Salesne 2016). Despite the lack of recorded visitor observation, the flower attributes of the Australasian O. splendida, which bears large, flared, white flowers that open nocturnally and release a strong fragrance, are very similar to that of Fagraea, renowned for its bat-pollination (Momose et al. 1998).
Fourth, the large variety of fruit morphology exhibited by *Oxera* suggests different dispersal agents, although these mechanisms have not been fully identified in the field (Table 1). We assume that the different behaviors and flight abilities of animal dispersers would have affected the spatial scale of gene flow, and thus produced different rates of genetic divergence between *Oxera* lineages, due to varied dispersal abilities and habitat selection of dispersers (Givnish 2010, Theim et al. 2014). The largest white fruits encountered in Australasia are consumed by bats and cassowaries (Richards 1990; Hutson et al. 1992; Cooper and Cooper 2004). Other large colored fruits (ca. > 2 cm) could be exclusively eaten by imperial pigeons (*Ducula*, Columbidae), which is the only bird able to swallow and effectively disperse such large fruits (Meehan et al. 2002; Carpenter et al. 2003; Cibois et al. 2017; P. Bachy pers. comm. for *O. palmatinervia*). It is noteworthy that the sedentary behavior of pigeons confines them mostly to forest understories (Colombo 2008; Wotton and Kelly 2012). Smaller fruits (ca. < 2 cm) are consumed by more diminutive birds such as Sturnidae (Table 1; Tassin et al. 2010), which probably move over short distances, but are able to shift between different vegetation types (Barré et al. 2006). Finally, large grey or brown fruits having armed appendages are considered to be consumed by large geckos (*Rhacodactylus, Mniarogekko, Correlophus* genera) because they are not discouraged by the fruits’ repelling structures (Whitaker and Bauer, pers. com.). Large geckos also have limited spatial movements (Wotton et al. 2016), which may have constrained gene flow in *Oxera*.

Given the large diversity of morphological traits, ecological attributes, and geographical ranges exhibited by *Oxera*, we suspect that species diversification within subclades of this genus has been driven by several ecological and biological factors acting at different time periods, that is in a leapfrog pattern (as originally defined by Chase and Palmer 1997). Available information on species coexistence within similar regions or habitats may also help test whether sympatric
speciation has occurred in relation to different pollination and dispersal niches. Indeed, such a scenario suggests that sister species with distinct biotic niches should co-occur either in the same region or habitat. Sister species divergence based only on ecological preference or geographic range would otherwise suggest that speciation mainly occurred through parapatric or allopatric speciation, respectively. We thus posit that phylogegetic patterns of species ranges and niches bear the signature of both selective and neutral forces as engines of clade diversification. Here we report the first detailed phylogenetic reconstruction of this exceptional radiation of Lamiaceae, the genus Oxera, within the New Caledonian biodiversity hotspot, and attempt to identify the major factors that have shaped its current species diversity. We used a combination of phylogenetics, molecular dating, and comparative analyses of species diversification and niche evolution in order to: (1) reconstruct the tempo and rate of species diversification in Oxera, (2) extricate and identify the different drivers of its diversification, (3) and appraise their respective effects. This study specifically asks a pivotal question: Is Oxera the single clear adaptive radiation in New Caledonia?

MATERIALS AND METHODS

Species Sampling and Molecular Datasets

In order to both establish species relationships and to estimate divergence times within the genus Oxera, the focal ingroup was composed of the 38 recognized species according to the most recent systematic investigations in New Caledonia (Gâteblé unpublished data, available at http://endemia.nc/flore/fiche588), and taxonomical revisions by de Kok and Mabberley (1999a, 1999b) for Australasia and Pacific. We added to the dataset the sister lineage Hosea, as well as 10 species belonging to the closely related Clerodendrum clade identified in Yuan et al. (2010). Three more divergent species of Lamiaceae were used as external outgroups (i.e. Ajuga
chamaepitys, Teucrium pyrenaicum, Rotheca sp. Wen 9487; Online Appendix 1a; Data available from the Dryad Digital Repository: http://dx.doi.org/10.5061/dryad.gb66n2). A total of 51 species were used in this sampling, which we refer to as the *Oxera* dataset, including 22 species with previously published sequences (downloaded from GenBank), and 29 species with new sequences generated for this study. This molecular dataset consisted of the 12 DNA loci sequenced in Barrabé et al. (2015). This allowed us to improve (1) the phylogenetic resolution, and (2) branch length estimates relative to Barrabé et al. (2015). All new DNA sequences were generated using the DNA extraction, amplification and sequencing protocols described in Barrabé et al. (2015). All accessions used in this study are listed in the Online Appendix 1a (available on Dryad).

For divergence time estimation, we also used two additional alignments composed of four DNA plastid regions (*matK, rps16, trnL-F* and *trnL-trnF*; Online Appendix 2a, available on Dryad) from two datasets, with taxon sampling that spanned the Lamiales and Lamiaceae. The Lamiales dataset included: (1) a subset of the *Oxera* dataset (i.e. five species; Online Appendix 1c, available on Dryad); and (2) 177 representatives of various lineages within Lamiales, whose sequences were downloaded from GenBank (Online Appendix 1c). The Lamiaceae dataset was thus composed of (1) the aforementioned *Oxera* subset, and (2) 59 taxa representing all major Lamiaceae lineages (downloaded likewise from GenBank; Online Appendix 1b, available on Dryad). This large-scale sampling allowed us to incorporate Lamiales and Lamiaceae fossils as calibration points (see below).

All DNA alignment matrices used in this study are available in Dryad (doi:10.5061/dryad.mm1fl40).

*Phylogenetic Inference*
For the three molecular datasets, phylogenetic inferences were conducted using Bayesian Markov Chain Monte Carlo (MCMC) as implemented in MrBayes v3.2.1 (Ronquist et al. 2012) based on single-locus and concatenated datasets. Best-fit nucleotide sequence evolution models were identified using jModelTest (Posada 2008) based on the Akaike criterion (more details on settings are provided in Online Appendix 2a, available on Dryad). The combined datasets were partitioned to allow each locus to possess specific model parameters (Nylander et al. 2004). The methodological approach of the Bayesian MCMC analyses followed that described in Barrabé et al. (2015) and the details of parameter settings are provided in Online Appendix 2b, available on Dryad. All analyses were run on the Cyber Infrastructure for Phylogenetic Research cluster (CIPRES; http://www.phylo.org/; last accessed October 18, 2017). The post-burn-in trees resulting from the MCMC stationary phase were used to construct a majority-rule consensus tree and calculate Bayesian posterior probabilities (PPs); clades were considered well-supported when PP values were ≥ 0.95). The three resulting consensus trees are available in TreeBASE (ID 23353) and Dryad (doi:10.5061/dryad.mm1ft40).

In order to check for phylogenetic incongruence between nuclear and plastid loci, we also ran two phylogenetic reconstructions separately for all six concatenated nuclear regions and all six concatenated plastid regions, using the same MrBayes parameter settings and models of nucleotide evolution as above. These two analyses were only applied to the Oxera dataset. We then assessed whether there was any supported (PP ≥ 0.95) incongruence between two trees.

**Fossil Dating and Divergence Time Estimation**

We performed a two-step approach to estimate the temporal evolution of Oxera. This allowed us to test the impact of different dating calibrations and taxonomic sampling on divergence time estimates. In the first step, we performed a fossil calibration on the Lamiales and
Lamiaceae datasets using fossils described in a recent Lamiaceae molecular dating study (Yao et al. 2016). We incorporated three Lamiaceae (Melissa, Ocimum, Stachys) and three Lamiales fossils (Bignoniaceae, Acanthaceae, Oleaceae) for dating the phylogeny inferred with the Lamiales dataset, and two Lamiaceae fossils (Melissa and Ocimum) for dating the phylogeny inferred with the Lamiaceae dataset (for further details on the design and parameters of these calibrations, see Online Appendix 2c, available on Dryad and explanations provided in Yao et al. 2016). For root calibrations we used divergence times estimated in Magallón et al. (2015): (1) the divergence between Lamiales and Gentianales – Solanales for the Lamiales dataset, and (2) the divergence between Plocospermataceae and other Lamiales for the Lamiaceae dataset. In the second step, the divergence time estimate between Rotheca (sp. Wen 9487) and other Lamiaceae recovered during the first step (i.e. the dating of the Lamiaceae dataset) was used as a secondary root calibration point (see results) for the Oxera dataset.

For the three molecular datasets, molecular divergence times were estimated using the Bayesian MCMC approach implemented in BEAST v.1.8.0 (Drummond and Rambaut 2007). DNA regions were combined and partitions were set as in the above Bayesian MCMC analyses (Online Appendix 2c, available on Dryad). An uncorrelated relaxed molecular clock model was selected following a lognormal distribution, and the Birth-Death process implemented for the tree prior. Other details on analyses, calibration and parameter settings are provided in supplementary data (Online Appendix 2c). The post burn-in trees were summarized, and Bayesian PPs, median height (= age estimate), and the 95% highest posterior density heights interval of each node (95% HPD) assessed, using a Maximum Clade Credibility target tree (named as MCCT tree for the Oxera dataset) in Treeannotator v.1.8.0 (Drummond and Rambaut 2007). For the Oxera dataset a subset of 100 dated trees (RD trees hereafter) were also randomly sampled from the stationary phase to integrate phylogenetic uncertainty in some of the following analyses (see below). All
divergence time analyses were conducted using CIPRES. The three resulting Maximum Clade Credibility trees are available in TreeBASE (ID 23353) and Dryad (doi:10.5061/dryad.mm1ft40).

**Comparative Analyses of Species Diversification**

To obtain an overall view of the *Oxera* diversification we first generated a lineage through time diagram, based on a pruned version of the MCCT tree including only *Oxera* species and a single sample per species (pMCCT tree), and also on the RD trees (pruned as in the pMCCT tree). We also calculated net diversification rates, following the conservative approaches implemented in Pillon (2012) and Barrabé et al. (2014), to allow comparisons with other oceanic insular plant radiations, using median crown ages and their 95% HPD estimated from the molecular dating, and two extreme values for relative extinction (null and equal to 0.9). Net diversification rates were likewise estimated per unit of area and log(area).

To assess more precisely the rate and tempo of species diversification in *Oxera* through time, we carried out diversification analyses with maximum likelihood (ML) and Bayesian modeling approaches. The ML analyses were conducted in the TreePar R package (Stadler 2011), using an optimisation algorithm to infer past rates of speciation and extinction and their temporal variation. We fitted various diversification models: a pure birth model, a constant birth-death model, several more complex models allowing one to several rate shifts through time (up to 10 shifts), and finally several diversity-dependent models. All models were fitted on the pMCCT tree (see Online Appendix 2d for further details on parameter settings, available on Dryad) and on the RD trees to account for phylogenetic uncertainty. The best-fit diversification model was identified using the corrected Akaike criterion, and a likelihood-ratio test was used for comparing nested pure birth, birth-death and rate shift models (LRT).

The Bayesian diversification analyses were computed using BAMM (Rabosky et al. 2014).
2014). This allows modelling complex dynamics of speciation and extinction on phylogenetic trees using a reversible jump MCMC algorithm. We pruned the MCCT tree in the same manner as the pMCCT tree, but retained species belonging to the Clerodendrum clade to assess early variation in Oxera diversification rates. The sampling fraction was completed with an estimate of species richness, especially for the Clerodendrum clade (retrieved from the Kew Checklist website: http://wcsp.science.kew.org; last accessed October 18, 2017). As we expected two rate shifts to have taken place during the evolution of Oxera and its relatives (considering the large sizes of the genera Clerodendrum and Oxera as compared to the other small genera), the prior on the number of diversification shifts was set to 2. All other priors were estimated in the BAMMtools R package (Rabosky et al. 2014), with the default settings used for all other parameters. The MCMC was run for $50 \times 10^6$ generations and sampled every 10,000 generations.

The analysis was conducted with three independent Markov chains. The first 25% (Oxera dataset) and 10% (Lamiaceae and Lamiales datasets) of each run was discarded after checking for chain convergence and adequate MCMC sampling. The remaining generations were summarized to generate the 95% credibility interval for rate shift configurations, the marginal shift probability tree (where branch lengths are proportional to the probability that a shift occurred on a given branch), the best rate shift configuration with the highest maximum a posteriori probability, the phylorate plot (showing variation of mean diversification rates with a colored gradient) and finally the rates-through time plots (only built for the Oxera focal group).

**Biological, Ecological and Geographic Range Datasets**

To identify and disentangle suspected drivers of species diversification in Oxera, we built a dataset by compiling data on five major life traits: (1) flower morphology, (2) fruit morphology, (3) life forms, (4) geographical occurrences, and (5) environmental preferences. The
flower and fruit morphology (i.e. organ dimensions, colours, shapes, and textures) were compiled from herbarium and fieldwork observations on organ dimensions, colours, shapes, and textures. Those traits were coded as 13 discrete and three continuous characters for flower morphology, and three discrete and three continuous traits for fruits (Online Appendix 3a, d, e, available on Dryad). The life form dataset was composed of a single discrete trait corresponding to the four life forms usually ascribed to Oxera, namely monocaulous, robust liana, slender liana and shrub / small tree (Online Appendix 3a, b). Note that no functional or physiological traits related to light requirements or nutrient use strategy were available for Oxera.

The geographical distributions of New Caledonian species were retrieved from the databases of the herbaria of Nouméa (NOU, VIROT), the Museum national d’Histoire naturelle of Paris (P, SONNERAT), the University of Zurich (Z), and additional field observations. The geographical coordinates of herbarium specimen records were then databased, error-corrected for distribution, and finally incorporated into a Geographical Information System (GIS) under QGIS 2.8.1. For Australasian and Pacific species distributions were assessed from de Kok and Mabberley (1999b) and manually added into the same GIS layer.

The environmental dataset was composed of three variables that best explain plant distributions across New Caledonia (Jaffré 1993; Morat 1993; Online Appendix 3a, c): geological substrates, vegetation types, and elevation. Species’ rock types were coded as occurring on ultramafic rocks, on volcano-sedimentary and metamorphic rocks, or ubiquists. These geological attributes were determined by coupling geographical occurrences with a layer of geological substrate provided by the Direction de l’Industrie, des Mines et de l’Energie de la Nouvelle-Calédonie (New Caledonia). Species’ vegetation types were coded as occurring in wet forests, in sclerophyllous vegetation types (i.e. dry forests and/or maquis vegetation), and ubiquists, based on herbarium and field observations (Gâteblé, pers. obs.). Species’ elevation ranges were
extracted from the GIS layer generated by a digital elevation model (resolution of 10 m) provided by the Direction des Infrastructures de la Topographie et des Transports Terrestres (New Caledonia), and then averaged across geographical occurrences of each species.

To identify ecological syndromes among *Oxera* species, we performed multivariate analyses on the environmental, flower, and fruit datasets. As we used both continuous and discrete traits, we conducted the PCA analyses by using the Hill and Smith (1976) principal component method under the ade4 R package (Chessel et al. 2004). This analysis allowed clustering species among pollinator syndromes, dispersal syndromes and habitat preferences, which we subsequently treated as new discrete traits according to the species clustering (i.e. the niche datasets; Online Appendix 3f, available on Dryad). We posit that the ecological syndrome of a species reflects the ecological niche it occupies (Johnson 2010, Pauw 2013). No data on species growth and architecture were available, we therefore could not evaluate life forms in a similar manner; this trait was treated as a discrete variable without any step of ordination analysis.

**Comparative Analyses of Niche Evolution**

To assess the mode and tempo of evolution of each niche during the *Oxera* radiation (i.e. of pollination and dispersal syndromes or habitat preferences), we measured their respective amount of phylogenetic signal by estimating $\kappa$ and $\lambda$ Pagel statistics (Pagel 1999). Values of $\kappa$ and $\lambda$ close to 1 indicate a strong phylogenetic signal and gradual trait evolution (i.e. according to a model of Brownian motion), and deviation from this expectation provides insight into temporal patterns of trait evolution. Values of $\kappa$ close to 0 depicts punctual evolution, where trait divergence occurs independently from branch lengths in the phylogeny. Values of $\lambda$ close to 0 reveal a low phylogenetic signal, where most trait change occurred late in evolutionary history.
and closely related species thus share very little trait similarity. For the habitat, pollination, and dispersal niches $\kappa$ and $\lambda$ statistics were estimated using the 'fitContinuous' and 'phylosig' functions of the geiger and phytools R packages, respectively (Harmon et al. 2008; Revell 2012). Estimations were performed on the RD trees, and by averaging estimated values for each of the first $n$ axes of each PCA explaining 90% of the cumulative variance. For life form, each statistic was simply averaged through the RD trees using the 'fitdiscrete' function (geiger) and the single discrete trait.

To reconstruct the evolutionary history of habitat preference, pollination, dispersal niches and life form, we conducted ancestral state reconstruction analyses. We first assessed ancestral niche states using the 'ace' function in the ape R package (Paradis et al. 2004) applied to the pMCCT tree, and the niche and life form datasets. We fitted three ML evolution models: the 'ER' (with equal state transition rates), 'SYM' (symmetrical), and 'ARD' (with all rates unequal) models, identifying the best-fitting model using comparisons performed on the corrected Akaike criterion, and likelihood ratio test. We then estimated their respective absolute shift number and timing by performing stochastic character mappings (Huelsenbeck et al. 2003), using the 'make.simmap' function in phytools. We launched 1000 simulations using an estimated prior distribution on the root node, the best-fit ML model recovered in the previous analyses and applied first to the pMCCT tree, and then to the RD trees to obtain most likely envelopes of past shift number for habitat preference, pollination, dispersal niches and life-forms. For 11 of the 100 RD trees, we encountered intractable optimization issues when using the 'make.simmap' function. We subsequently removed the 11 trees from these analyses and used only 89 RD trees. Absolute shift timings were extracted using a custom R-script from all simulations and summarized by plotting the median number of state changes in different time bins of a 0.5 Myr time-grid.

To investigate whether a particular niche state (pollination, dispersal or habitat) or life-
form would have affected clade diversification rates of *Oxera*, we conducted multi-state trait-based analyses that estimated simultaneously trait-dependent speciation, extinction, and transition rates on a phylogeny and character distribution (Fitzjohn et al. 2009). These were performed using the 'make.musse' function under the diversitree R package (Fitzjohn et al. 2009), applied to the pMCCT tree, and the niche and life form datasets. We first fitted 17 models from a null model (rates independent of trait states) to a full model (all rate components dependent of trait states; Online Appendix 4, available on Dryad), conserving the best-fitting using the corrected Akaike criterion. We performed subsequent Bayesian analyses through a MCMC, run for 10,000 generations, seeding them with rate estimates recovered from the previous ML analyses as priors, and discarding the first 1000 generations as burn-in. Posterior probability distributions of all parameters were summarized using the diversitree R-package. We also fitted the best model and compared it to the second best model across all RD trees to check that model selection was robust to phylogenetic uncertainty.

*Geographical Evolution vs. Habitat Evolution*

To investigate the relative roles of geographical and environmental divergence during the diversification of *Oxera*, we computed age-range correlations (Fitzpatrick and Turelli 2006; Warren et al. 2008) where metrics of range overlaps, range asymmetries, and habitat distances computed between species pairs are compared to their estimated time of divergence (from the phylogeny). These metrics have been recurrently used to diagnose different speciation and post-speciation scenarios (Anacker and Strauss 2014; Grossenbacher et al. 2014).

Species geographical ranges were retrieved from the geographical dataset by creating for each species a single convex polygon enclosing its locations using the 'convex hull' tool under QGIS. For narrow endemic species, with one or two occurrences, we applied a buffer of 0.5 km
around each location, and used a range of $3.141592 \times 0.5^2$ km$^2$ for the former, and of $6.283184 \times 0.5^2$ km$^2$ for the latter. From these distribution data, range overlaps, range asymmetries and habitat distances metrics were computed between all possible pairs of species. Range overlap was defined as the area occupied by two species divided by the area of the more narrowly ranging species, ranging from 0 (no co-occurrence) to 1 (complete co-occurrence). Range asymmetry was calculated as the area of the wider-ranging species divided by that of the smaller (ranging from 1 to infinity). The habitat similarity between two species was assessed by calculating their euclidian distance (habitat distance) based on the eigenvector values of the first n axes explaining 90% of the cumulate variance retrieved from the environmental PCA (see above). These geographical variables (areas of all *Oxera* species, range asymmetries and range overlaps of all *Oxera* species pairs) are available in Dryad (doi:10.5061/dryad.mm1ft40).

Age-range correlation analyses were performed using an extended version of the 'age.range.correlation' function of the phyloclim R package (Heibl and Calenge 2013; https://github.com/danlwarren/arc-extensions/blob/master/age.range.correlation.2.R; last accessed October 18, 2017), applied to our pMCCT and the RD trees. We launched 1,000 iterations for the Monte Carlo resampling procedure to create the null hypothesis of no relationship between phylogenetic relatedness and range overlap, range asymmetry, or habitat distance, and tested it. We calculated linear regressions, whose slopes and intercepts indicate speciation mode (allopatric vs. sympatric) or habitat evolution (conservatism vs. divergence) through time. For each metric a 'super-p-value' was calculated, corresponding to the tree proportion across the RD trees for which the linear regression was significant. We also assessed the frequency of range overlaps across all random species pairs and across all sister species pairs using a kernel density plot.

Finally we estimated the respective importance of geographical vs. habitat divergence and whether local co-existence is possible between closely related *Oxera* species. To do so, we
superimposed species geographical overlaps to their habitat preferences (summarized into diagrams combining information on their geological, elevation and vegetation attributes) within each Oxera subclade (as delimited in Barrabé et al. 2015) to determine whether closely related species could possibly occur in sympatry.

Results

Phylogenetic Inference

The Bayesian MCMC analyses of the three species sampling (Lamiales, Lamiaceae and Oxera datasets) recovered the same following robust phylogenetic relationships (Online Appendices 5–7, available on Dryad). The sister genera Hosea and Oxera formed a well-supported clade that was sister to the Clerodendrum clade (PP=1). Analyses based on the Oxera dataset provided more resolution and detail on the internal Oxera relationships, which are congruent with the ones established in Barrabé et al. (2015) (Online Appendix 5). The Australasian O. splendida was placed as sister to the New Caledonian radiation (PP=0.72), which included all New Caledonian and nested Pacific subclades. We retrieved seven well-supported New Caledonian subclades (PP=1; Fig. 2a), namely the oblongifolia, neriifolia, pulchella, baladica, subverticillata, robusta, and sulfurea subclades.

A few supported incongruences (PP ≥ 0.95) were observed between the phylogenetic trees reconstructed separately from the six nuclear loci and from the six plastid loci (Online Appendix 8, available on Dryad), but these incongruencies were all located near the tips (i.e. between close species). This discordance did not affect the robustness of the seven New Caledonian subclades previously recovered. These minor incongruences underscore the importance of accounting for phylogenetic uncertainty by using the 100 RD trees in most of our evolution and geographical analyses (see material and methods).
**Molecular Dating**

The three molecular BEAST dating analyses provided congruent divergence times for *Oxera* and relatives (Figs 2a, Online Appendices 9–11, available on Dryad), which can thus be considered as a reliable appraisal of colonization dates and tempo of species diversification. *Oxera* likely emerged during the late Miocene, and the New Caledonian radiation sensu stricto is estimated to have initiated during the early Pliocene. The median divergence time estimates for the stem node of *Oxera* were 11.46 Ma (95% HPD = 5.65-19.68), 11.2 Ma (95% HPD = 5.61-19.06), and 12.02 Ma (95% HPD = 6.21-19.16), as recovered with the Lamiales, Lamiaceae, and *Oxera* datasets, respectively (Figs 2a, Online Appendices 9–11). For the crown node, age estimates were 6.34 Ma (95% HPD = 2.89-11.48), 6.28 Ma (95% HPD = 3.07-10.73), and 5.39 Ma (95% HPD = 2.97-8.42), respectively. The *Oxera* dataset provided an estimate of 4.54 Ma (95% HPD = 2.7-6.92) for the crown node of the New Caledonian radiation (Fig. 2a).

**Oxera Diversification**

The lineage through time plot highlighted a gradual and exponential increase of the number of *Oxera* lineages through time (Fig. 2a). The net conservative diversification rates are summarized in Tables 2 and 3. For the New Caledonian radiation, these rates were 0.2 species/myr for a null extinction and 1.04 species/myr for an extinction of 0.9. With respect to per-unit-area and per-unit-log(area) they were estimated between $1.1 \times 10^{-5}$ and $5.6 \times 10^{-5}$ species/myr/km², and between 0.02 and 0.106 species/myr/log(km²), respectively. The BAMM analyses inferred two early instances of changes in the diversification rate. The phylorate plot showed an increase in mean diversification rates at the crown node of *Oxera* and the second deepest node of the *Clerodendrum* clade, whereas *Hosea* demonstrated a decrease in these rates.
Barrabé L., Lavergne S., Karnadi-Abdelkader G., Drew B., Birnbaum P. and Gâteblé G.

(Online Appendix 12a, available on Dryad). Five of the six most probable 95% credible rate shift configurations (with a cumulative PP of 0.378; Online Appendix 13, available on Dryad) showed significant rate shifts mainly located on the two consecutive branches leading to the New Caledonian Oxera radiation, and those leading to most of the Clerodendrum clade (Online Appendix 13). Both shifts were depicted in the marginal shift probability tree, where these latter branches were significantly longer than most others, indicating a high probability that these shifts occurred on their respective branches (Online Appendix 12b, available on Dryad). The Oxera rates-through time plots highlighted that speciation rates remained constant (with a mean value of ca. 0.71 species/myr). Extinction rates decreased slightly at the radiation onset but remained constant after (mean value of ca. 0.31 species/myr). The resulting net diversification rates increased early in the radiation onset and later remained quite constant (mean value of ca. 0.4 species/myr; Figs 2b, Online Appendix 12c, available on Dryad). The ML diversification analyses selected the pure birth model as best-fitting our data for the genus Oxera, with a net diversification rate of 0.575 species/myr (Online Appendix 14, available on Dryad). Accordingly, the pure birth model was the best selected model on 93% of the RD trees.

Niche Ordination

The multivariate analyses allowed the separation of four, three, and five clearly distinct ecological syndromes from the species’ environmental, flower and fruit datasets, respectively (Fig. 1c). The first four, nine and six axes of the PCA analyses (explaining 90% of the cumulative variance), respectively, were retained for subsequent comparative analyses. The three major habitats occupied by Oxera were forests on non-ultramafic rocks, forests on ultramafic rocks, sclerophyllous vegetation, and a fourth class was defined for ubiquist species. The three pollination syndromes characterized species with actinomorphic, gullet, and bilabiate floral
morphs each adapted to bat, bird, moth/butterfly pollination, respectively. For dispersal syndromes the PCA axis markedly separated species with small fruits ≤ 2 cm (on the left) from those with large fruits > 2 cm (on the right; Fig. 1c). The five dispersal syndromes discriminated species with potato-like (consumed by cassowaries and bats), paddle-like (by Columbidae), small rounded (by Columbidae and/or small birds such as Sturnidae), large rounded (by Columbidae), and thorny fruit morphs (presumably by large geckos).

**Niche Evolution**

Our estimates of both Pagel statistics showed distinct evolutionary patterns (Fig. 2c; Online Appendix 15, available on Dryad). We found low values of $\lambda$, indicating low phylogenetic signal (i.e. a recent accelerated evolution), for the habitat preference (Fig. 2c), and high phylogenetic signal for the dispersal niche and life form, suggesting that these niche characteristics have diversified early. For the pollination niche, estimates of $\lambda$ were more spread out, with a lower 5% quantile of 0.2, a higher 95% quantile of 1.01, and a median value of 0.99; this also indicated a relatively high phylogenetic signal (Fig. 2c). Estimates of the $\kappa$ statistic were close to 0 for the habitat preference (indicating a punctual evolution), and close to 1 for the dispersal niche and life form, respectively (indicating more gradual evolution). For the pollination niche, $\kappa$ scaled between 0.35 (5% quantile) and 0.99 (95% quantile), with a median value of 0.69.

The best-fit evolutionary model identified in our ancestral state reconstruction analyses was the 'ER' model for each niche/trait dataset (Online Appendix 16, available on Dryad). The reconstructed ancestral habitat preference of *Oxera* was ambiguous: forests on both ultramafic and non-ultramafic rocks were together reconstructed with a high likelihood (forested vegetation was recovered as ancestral for this node with cumulated likelihoods of both forest types of ca.
0.57). However, the ancestral pollination, dispersal, and life form was inferred with much less ambiguity; the Oxera ancestor was very likely a robust liana with gullet flowers producing small rounded fruits (Online Appendix 17, available on Dryad). Analyses of stochastic character mapping allowed us to estimate that very few pollination, dispersal, and life form shifts occurred during the evolution of Oxera (up to two shifts per time bin of 0.5 myr; Fig. 2b), and that most of these trait shifts occurred between 2 Ma and 0.5 Ma for pollination, and following 3 Ma and 3.5 Ma for dispersal and life form, respectively. Habitat shifts occurred between 9 Ma and present, but from 4 Ma onward their number increased markedly, finally reaching 17 shifts between 0.5 Ma and the present.

The best-fitting model of trait-dependent species diversification identified for habitats had speciation and transition rates all equal, a null extinction rate (Online Appendix 4), and no discernible effect of any habitat type. For the pollination syndromes, dispersal types and life forms, the best-fitting model was that with a null extinction, transition rates all equal, and a particular character state in which speciation rates were significantly different from other states (Online Appendix 4). These results were very robust to phylogenetic uncertainty, as 100% of the RD trees consistently yielded the same best models. Slender lianas had on average significantly higher speciation rates comparing to other life forms, actinomorphic flowers and potato-like fruits had on average significantly lower speciation rates comparing to other floral and fruit types (Online Appendix 18, available on Dryad).

**Geographical Evolution**

The range overlap between all species pairs was generally low (mean value of 0.187, and a standard deviation of 0.357), suggesting a high level of allopatry between all species. The kernel density plot highlighted two range overlap frequency peaks, the highest located for a range
overlap of 0 and the shortest to 1 (Fig. 3). Age range correlation analyses showed that the slope of range asymmetry through time was significantly positive for linear regressions (all p-values < 0.05 across RD trees, Online Appendix 19, available on Dryad). For range overlap and habitat distance, linear regression slopes with divergence times were negative in both cases but not significant.

Different Oxera subclades highlighted distinct patterns of geographical overlap (Fig. 4a, b). The baladica subclade was entirely and strictly allopatric since none of its species overlapped geographically. The oblongifolia subclade was completely sympatric as all its species overlapped. The other subclades (i.e. 'neriifolia', 'pulchella', 'robusta', 'subverticillata', and 'sulfurea' subclades) exhibited more complex patterns (Fig. 4a). Overall, of the 96 possible pairs of species encountered within the seven New Caledonian subclades, we recorded 23 cases of partial or entire geographical overlap (Fig. 4a, b), but most of them involved species occurring in markedly distinct habitats. In fact, among all 96 species pairs, only five pairs involved geographically overlapping pairs of species growing in the same habitat, suggesting possible local co-existence (i.e. O. oblongifolia and O. glandulosa, O. coriacea and O. palmatinervia, O. merytifolia and O. subverticillata, O. gmelinoides and O. pancheri). None of these species pairs have, however, been observed co-occurring in the field (Gâteblé, pers. obs.).

DISCUSSION

An Early Burst of Diversification

Our study shows that the genus Oxera is a quite recent and rapid plant radiation that initiated during the late Miocene, and that most of the New Caledonian subclades within Oxera began to diversify in the early Pliocene (Table 2, Fig. 2). It is noteworthy that this New Caledonian radiation occurred long after the emergence of Grande Terre about 37 Ma (Cluzel et
Thus, the radiation of Oxera originated in the archipelago via long-distance or stepping-stone dispersal, but was not triggered by Gondwanan fragmentation. This continental dispersal to the New Caledonian archipelago was probably aided by the ancestral dispersal type (i.e. small rounded fleshy fruits; Online Appendix 17), which may be the most efficient dispersal mode in the group. Following this dispersal to New Caledonia, the successful establishment of ancestral Oxera may have been facilitated by the climbing habit of its ancestor (robust woody liana identified as the ancestral state; Online Appendix 17), which is believed to allow the occupation of a broad range of local environments (Gianoli 2004). The finding that the ancestral colonizer of extant New Caledonian Oxera was reconstructed as having a liana life-form with fleshy fruits makes it a quite unique case since the liana form is generally associated with wind dispersal (Givnish 2010), implying dispersal limitations over water, and that the liana niche in islands remains often empty.

Diversification analyses identified an early burst of diversification (BAMM analyses; Fig. 2a, b, Online Appendix 12), likely located between the divergence of the Oxera ingroup and its sister lineage Hosea (ca. 12 Ma) and the crown node of Oxera within New Caledonia (ca. 4.5 Ma). This late Miocene/early Pliocene burst of species diversification indicates that Oxera underwent an initial period of rapid cladogenesis, especially in New Caledonia, concordant with an initial decreasing of extinction rates; Figure 2b, Online Appendix 12. This coincides with the origination and early diversification of other major New Caledonian radiations (e.g. Psychotria clade NC2), and especially lineages typical of sclerophyllous vegetation types (e.g. Thiollierea; Table 2).

This period of intense species diversification is concordant with the global onset of Pliocene glaciations (Zachos et al. 2001) as well as the temperature declines and severe aridification recorded in the South Pacific during the Pliocene (Karas et al. 2011). It also
coincides with the timing of intense soil morphogenesis and weathering which is estimated to have occurred around 5.5 Ma in New Caledonia (Fig. 2a, b; Chevillotte et al. 2006). Such climatic events have been suggested to have impacted the evolutionary history of many plant lineages by leading to the extinction of certain species (thus alleviating competitive effects), and the emergence of new biotas (e.g. more sclerophyllous and open vegetation), especially since the Miocene (Donoghue and Edwards 2014). It is important to note that some of these novel habitats exhibit a patchy spatial distribution, which has likely increased genetic divergence. This ostensibly has generated vacant niches, created ecological opportunities, increased spatial divergence and thus triggered speciation in many Australasian lineages, as highlighted in Australia for Banksia, Eucalyptus and Allocasuarina (Crisp et al. 2004; Gallagher et al. 2013). The early rapid diversification of Oxera suggests that similar climatic and physical events fostered diversification within Oxera shortly after its arrival into New Caledonia.

An Explosive Species Diversification, with Early Divergence in Biotic Niches

The rate of species diversification estimated for Oxera is exceptionally high, and represents the fastest known New Caledonian plant radiation, rivalled only by Thiollierea (Manns et al. 2012; Table 2). Estimated speciation rates within Oxera are comparable to the fastest island plant radiations documented in previous studies (e.g. Bidens in Hawaii or Echium in Macaronesia; Table 3). The detected early burst of diversification has been followed by a rather constant diversification, as inferred from BAMM and ML Treepar analyses even under weak divergence origination scenarios (Online Appendices 12, 14); this may reflect the ongoing challenge within the evolutionary biology community to realistically model diversification processes, especially extinction (Stadler 2011; Morlon 2014). Nevertheless, it seems that since its origination Oxera has continued to diversify under constant speciation and rather null extinction,
as exemplified by the exponential increase of species lineages through time (Fig. 2a).

Trait-dependent diversification models suggest that no specific adaptation has disproportionately favoured speciation in Oxera (all biotic traits had equal speciation rates; Online Appendices 4, 18), excepting perhaps the slender liana life form (acquired with the emergence of the neriifolia, pulchella and oblongifolia subclades; see Table 4, Fig. 2a, Online Appendix 18), which is found in open sclerophyllous vegetation and exhibits high speciation rates probably because open habitats have increased in concert with Pliocene and Pleistocene cooling while remaining spatially fragmented (see below). However, the proliferation of species within Oxera might be related to the capacity of the genus to adopt different growth forms and floral and fruit morphologies, as hypothesized for angiosperms in general (Ricklefs and Renner 1994), probably in response to varied ecological opportunities available after its colonization of New Caledonia.

The early diversification of Oxera seems to have been mainly associated with niche shifts driven by pollination syndromes, dispersal strategies, and life-form variety (Fig. 2b). This suggests that the early diversification burst within the clade coincides with ecological diversification, particularly in regards to pollen vectors, dispersal agents, and light requirements. Although it is not possible to determine whether these niche shifts were directly involved in the process of lineage divergence (ecological speciation), or have rather been caused by post-speciation adaptation to diverse ecological opportunities, these results suggest that diverse ecological opportunities have likely facilitated the diversification of Oxera within New Caledonia. The decelerated diversification of pollination syndromes, dispersal niches, and life-forms (revealed by a rather high phylogenetic signal; Fig. 2c) likely indicates that all or most of these niches previously vacant were ultimately filled during the early history of the clade. Our comparative analyses indicate that from the late Pliocene to early Pleistocene, the major Oxera
lineages (i.e. the seven New Caledonian subclades plus *O. morierei*) had already originated (Fig. 2a), most of them occupying a unique niche combination. It is important to note that all recovered *Oxera* subclades were robust to contrasting phylogenetic signal between nuclear and plastid genes (Online Appendix 8). Hence each *Oxera* subclade robustly holds a unique trait combination (Table 4), excepting perhaps the *neriifolia* and *oblongifolia* subclades, which similarly exhibit slender lianas, bilabiate flowers and small rounded fruits. This evolutionary divergence in life forms seems not to be correlated with habitat divergence, since these two characteristics have evolved largely independently across *Oxera* (Fig. 2b, c), suggesting that different growth forms occupy distinct functional niches related to light requirements within habitats.

Our study thus detected strong ecological segregation among *Oxera* subclades and species (Fig. 1c), but the precision of our morphological data may not be sufficient to discriminate finer ecological syndromes encountered in *Oxera*. Compared to our results, the genus may exploit an even larger diversity in pollinators and dispersers than highlighted in this study. For example, the actinomorphic flowers of Pacific species are sometimes visited by honeyeaters (Belcher and Sibson 1982; de Kok 1997). Gullet flowers with small and narrow tubes, such as the ones of *O. sessilifolia*, *O. garoensis*, and *O. doubtiae*, may be more efficiently pollinated by Diptera or Coleoptera rather than birds (Jourdan, pers. comm.). It would be illuminating to conduct detailed investigations on the pollination biology of different *Oxera* species using more precise measurements of floral morphology characters. This could reveal that pollination syndromes have in fact spurred diversification during the evolution of *Oxera*.

*Recent Diversification Driven by the Interplay of Habitat Shifts and Allopatry*

Our comparative analyses further suggest that since the end of Pliocene and the onset of
the Pleistocene, the diversification of *Oxera* has been impacted by several punctual shifts in habitat preference (Fig. 2b, c). These events coincided with another intense period of soil morphogenesis and weathering events in New Caledonia which occurred between 3-2.5 Ma (Fig. 2a, b; Chevillotte et al., 2006), as well as several climatic oscillations documented in the southwestern Pacific (Dodson and MacPhail 2004). These events have likely caused myriad spatial rearrangements of New Caledonian biotas (Hope and Pask 1998, Stevenson et al. 2001, Stevenson 2004; Stevenson and Hope 2005), thus generating novel ecological opportunities, and hence the recent diversification of *Oxera*.

Phylogenetic patterns of geographic range overlap and asymmetry between pairs of species show that geographical isolation seems to have played a prominent role during the diversification of *Oxera*. This suggests that neutral divergence may have been at least as important as ecological speciation. Most species pairs within *Oxera* have clear allopatric distributions (null range overlap more frequent through all species pairs; Fig. 3). This is exemplified by the *baladica* subclade, which appears to have diversified almost entirely in allopatry (Fig. 4). Few species pairs clearly originated from sympatric speciation, as suggested by complete range overlaps and trait divergence (Figs 3, 4). Except for the *oblongifolia* subclade, the geographical range overlap between species remains remarkably low (< 0.4; Online Appendix 19) indicating that given the recent radiations of *Oxera*, most sister species have remained in allopatry, and that secondary sympatry may not have yet occurred in most sister species pairs.

The examination of geographic and ecological overlap between species pairs suggests that local species coexistence may in fact be very rare in *Oxera*. Among the 96 putative pairs of sister species (within the seven New Caledonian subclades), only five pairs potentially coexist locally, although this has never been noted after years of field observations (Gâteblé, pers. obs.). For example in the *oblongifolia* subclade (which exhibits largely sympatric species), each species
grows in a specific set of environmental conditions, excepting the ubiquitous *O. oblongifolia* (Fig. 4). Contemporary species coexistence is probably prevented by the recent interplay of allopatry and parapatry due to habitat shifts and environmental oscillations that have caused cycles of forest expansion and retraction. With *Oxera* being mainly a forest-adapted group (25 of 38 species confined to forests, and forest habitat identified as ancestral; Online Appendix 17), it is likely that vegetation cycles along the complex topographical gradients of New Caledonia have triggered spatial divergence and probably speciation. This process has been further amplified by the limited dispersal ability of *Oxera* since its dispersers are relatively sedentary. Such processes of vegetation oscillations along steep physical gradients, sometimes creating barriers to dispersal, is now considered to be a major driver of clade diversification, as demonstrated in recent theoretical simulations (Aguilée et al. 2012).

**CONCLUSION: IS Oxera A CLEAR ADAPTIVE RADIATION FROM NEW CALEDONIA?**

The genus *Oxera* constitutes a remarkable example of a rapid diversifying lineage that originated from a single ancestor. We observed that the group experienced an early burst of species diversification, followed by an exceptionally high and constant species diversification rate (Fig. 2b). This signature is considered typical of adaptive radiations for some authors (Guyer and Slowinski 1993; Slowinski and Guyer 1993; Soulebeau et al. 2015) but not all (Givnish 1997, 2015), mainly because it is usually thought that early diversification bursts are driven by the exploitation of new ecological opportunities, which allows lineages to enter new adaptive zones. The early history of *Oxera* seems to have been paved by niche shifts toward novel pollination, dispersal and life-form traits. These niche shifts later decelerated, perhaps due to a saturation of available niche space. However, our analyses do not highlight any diversity dependent diversification processes, which are often considered as another hallmark of adaptive
radiations (Rabosky 2009). This is likely because other ecological opportunities have helped further diversification of the group after its initial phase of biotic niche exploration. More recent opportunities likely emerged through landscape formation and environmental oscillations which may have triggered allopatric and parapatric speciation processes. In fact, the explosive diversification of Oxera within New Caledonia appears to have been triggered by varied ecological opportunities during the course of evolution. Adaptive radiation should not be narrowly defined through quantitative tests or by quantifying diversification tempos, since some well-known adaptive radiations have little or no effect on speciation, or even a negative effect (Givnish 2015), and are therefore more identified by high rates of morphological and ecological diversification (Givnish 1997; Sanderson 1998); this remains to be investigated for the Oxera diversification.

The explosive radiation experienced by Oxera thus constitutes a remarkable model for studying the drivers involved in the evolution of the New Caledonian flora, especially for recent epochs. The genus is an unclassifiable, multifaceted radiation seemingly triggered by both adaptive and neutral processes (adaptive, geographical, climatic, etc.), and driven by several classes of biotic and abiotic factors. Oxera could be therefore regarded as a partial adaptive radiation since changing ecological opportunities have contributed to its radiation, with an early diversification of biotic traits (life-form, pollination, dispersal), but more recently driven by the joint action of habitat changes and allopatric speciation leading to scant local coexistence between species. Although different diversification drivers may have been overlapping in time, the early stage of Oxera diversification could be then viewed as a leapfrog radiation (sensu Chase and Palmer 1997), where diversification drivers have relayed to one another at different time periods, but geographic processes may have later been an equally important driver of speciation. Indeed, past climatic history of New Caledonia has also acted as a major evolutionary force, with
two pivotal events, a dramatic aridity at the early Pliocene leading to the release of newly vacant niches, and the accentuation of glacial-interglacial cycles from the early Pleistocene, causing repeated biota rearrangements. From our study, it is legitimate to ask whether any other case of adaptive radiation can be clearly demonstrated in old islands system such as New Caledonia, since the distinctive hallmark of past adaptive divergence is progressively blurred by more recent environmental fluctuations creating new ecological opportunities.

DATA AVAILABILITY OF SUPPLEMENTARY MATERIAL

Data available from the Dryad Digital Repository:

http://dx.doi.org/10.5061/dryad.gb66n2 for Online Appendices and from http://dx.doi.org/10.5061/dryad.mm1ft40 for DNA alignment matrices and geographical variables. The resulting trees are available from TreeBASE (ID 23353).

ACKNOWLEDGEMENTS

We would like to thank all the people who provided plant material, access to specimens or bibliography: Laurence Ramon, Chanel Sam and Stéphanie Stephens (PVNH); Felix Forest, Edith Kapinos and Helen Fortune Hopkins (K); Vicki Funk and Carol Kelloff (US); Darren Crayn (CNS); Josephine Milne and Wayne Gebert (MEL); David Middleton and Nura Abdul Karim (SING); Jérôme Munzinger and Jacqueline Fambart-Tinel (NOU); Christiane Anderson (MICH); and the IAC’s team, especially Jacqueline Ounémoa, Virginie Lemay, Donny Wamytan, Laurent Demaret, Michel Moenteapo, Edmond Poitchili, Nicolas Anger, Hervé Vandrot and Hélène Udo, for having collected, propagated and grown all New Caledonian Oxera species over the past 10 years. Jim Leebens-Mack kindly allowed us to use the 1Kp data for the Oxera species. We thank Daniel and Irène Létocart, Neil Sleddon, Druce Horton and Kartuz
Greenhouses for providing us with pictures of Oxera and habitats. Armelle Tardivel is also thanked for arranging the figures of this manuscript. We are also grateful to Daniel and Irène Létocart and Dominique Fleurot for their unconditional assistance in the field. We also thank the relevant New Caledonian authorities (Direction de l’Environnement de la Province Sud, Direction du Développement Economique et de l’Environnement de la Province Nord and Direction du Développement Economique de la Province des îles Loyauté) and the Vanuatuan Department of Environmental Protection and Conservation for collecting permits. The authors are very grateful to Julien Renaud, Nicolas Fernandez and Damien Georges, who greatly helped on the SIG development, and the analyses computations under R. Some computations presented in this paper were performed using the CIMENT infrastructure (https://ciment.ujf-grenoble.fr), which is supported by the Rhône-Alpes region (GRANT CPER07_13 CIRA: http://www.cira.org) and France-Grille (http://www.france-grilles.fr). Finally, we thank Yohan Pillon (IRD) for his corrections and useful comments on the manuscript, as well as Vincent Savolainen, James Rosindell and Tom Givnish for their constructive evaluation of our manuscript.

REFERENCES


Barrabé L., Lavergne S., Karnadi-Abdelkader G., Drew B., Birnbaun P. and Gâteblé G.


Cluzel D., Maurizot P., Collot J., Sevin B. 2012. An outline of the geology of New Caledonia; from Permian-Mesozoic Southeast Gondwanaland active margin to Cenozoic obduction and supergene evolution. Episodes 35:72–86.

Colombo R. 2008. Stratégies de dispersion chez quelques espèces de Sapotaceae de Nouvelle-Calédonie. Implications pour la conservation des forêts humides. Nouméa: Institut de Recherche pour le Développement, Université de Montpellier II.


Drummond A.J., Rambaut A. 2007. BEAST: Bayesian evolutionary analysis by sampling trees.
Barrabé L., Lavergne S., Karnadi-Abdelkader G., Drew B., Birnbaum P. and Gâteblé G.


THE RADIATION OF NEW CALEDONIAN OXERA


en Nouvelle-Calédonie. Paris: ORSTOM.


THE RADIATION OF NEW CALEDONIAN OXERA


Barrabé L., Lavergne S., Karnadi-Abdelkader G., Drew B., Birnbaun P. and Gâteblé G.


THE RADIATION OF NEW CALEDONIAN OXERA


Slowinsky J.B., Guyer C. 1993. Testing whether certain traits have caused amplified diversification - an improved method based on a model random speciation and extinction. Am.
Barrabé L., Lavergne S., Karnadi-Abdelkader G., Drew B., Birnbaum P. and Gâteblé G.

Nat. 142:1019–1024.


FIGURES

Figure 1. Biological and ecological datasets of Oxera. a) Illustration of habitat preferences and biological syndromes, from top to bottom: habitat preferences (UM = ultramafic soils, NUM = non-ultramafic soils), pollination niche, dispersal niche. b) Illustration of life forms. c) Niche syndromes inferred from the Hill and Smith principal component method, according to the first two axes of multivariate analyses.

Figure 2. Evolutionary history of Oxera in New Caledonia, and of its habitat preferences, pollination and dispersal niches, and life forms. a) BEAST chronogram of the Oxera dataset with superimposed lineage through time plot. Median age estimates and blue nod bars (corresponding to the 95% highest posterior densities) are indicated for each node of interest. Bayesian posterior probabilities (PP) from the BEAST analyses (on the right) and MCMC Bayesian analyses (on the left) are indicated with an asterisk for each node of interest when > 0.95, and with a hyphen when < 0.95. Vertical light grey rectangles indicate periods of intense weathering as inferred from Chevillotte et al. 2006. b) Absolute shift timings of the three niches and life forms inferred from stochastic character mappings, with global delta $^{18}$O variation through time (in grey; from Zachos et al. 2001) and net diversification rate variation through time of Oxera, as inferred from BAMM analyses (in dark blue), superimposed. c) Phylogenetic signal for habitat preferences, pollination and dispersal niches and life forms inferred from estimations of the $\kappa$ and $\lambda$ Pagel statistics.

Figure 3. Kernel density plot of range overlap through all possible species pairs (in black) and all possible sister species pairs (in grey) in Oxera.

52
Figure 4. Species coexistence within Oxera, indicated by subclade, with stars indicating likely coexistence; mapped on the BEAST maximum credibility clade chronogram from the Oxera dataset. a) Geographical overlap between all species of each subclade. b) Ecological ranges of all species indicated per subclade, plotted according to their altitudinal ranges and their habitat preferences (UM = ultramafic soils, NUM = non-ultramafic soils). Species names are indicated with the following abbreviations, listed according to subclade: robusta subclade (cori = O. coriacea, coro = O. coronata, lon = O. longifolia, pal = O. palmatinervia, rob = O. robusta), subverticillata subclade (aur = O. aureocalyx sp. nov. ined., mer = O. merytifolia, sub = O. subverticillata, tiw = O. tiwaeana sp. nov. ined.), sulfurea subclade (gme = O. gmelinoides, mic = O. microcalyx, oua = O. ouameniensis sp. nov. ined., pan = O. pancheri, rug = O. rugosa, sul = O. sulfurea), baladica subclade (bal = O. baladica, anu = O. aff. nuda, dou = O. doubetiae sp. nov. ined., gar = O. garoensis sp. nov. ined., oun = O. ounemoae sp. nov. ined., pap = O. papineau sp. nov. ined., ses = O. sessilifolia, van = O. vanuatuensis), neriifolia subclade (neri = O. neriifolia, ova = O. ovata, sor = O. sororia), pulchella subclade (bal = O. balansae, balV = O. aff. balansae, bre = O. brevicalyx, pul = O. pulchella), oblongifolia subclade (cra = O. crassifolia, gla = O. glandulosa, obl = O. oblongifolia, ore = O. oreophila).
Table 1. *In situ* direct observations of flower visitors and fruit consumers of *Oxera*.

<table>
<thead>
<tr>
<th>subclade</th>
<th>species</th>
<th>flower visitor (multivariate analyses)</th>
<th>flower visitor</th>
<th>fruit type (multivariate analyses)</th>
<th>fruit consumer</th>
<th>fruit type (multivariate analyses)</th>
<th>maximum mericarp length</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australasian <em>Oxera</em></td>
<td><em>Oxera splendida</em></td>
<td>actinomorphic</td>
<td></td>
<td>Cassowaries, flying foxes, rats</td>
<td>potato</td>
<td>62.5</td>
<td></td>
<td>Richards 1990, Mickelburgh et al. 1992, Cooper and Cooper 2004</td>
</tr>
<tr>
<td>Pacific <em>Oxera</em></td>
<td><em>Oxera amicorum</em></td>
<td>actinomorphic (Myzomela cardinalis, Gymnomyza viridis)</td>
<td></td>
<td>Columbidae (Ducula pacifica, Didunculus strigirostris), flying foxes</td>
<td>rounded</td>
<td>41.7</td>
<td></td>
<td>Belcher and Sibson 1982, de Kok 1997, Beichle 1987, Trail, 1994, Pillon pers.obs.</td>
</tr>
<tr>
<td>Pacific <em>Oxera</em></td>
<td><em>Oxera lehuntee</em></td>
<td>Honey eater (Glycifohia undulata), Zosteropidae (Zosterops sp.)</td>
<td></td>
<td>rounded</td>
<td>paddle</td>
<td>30.5</td>
<td></td>
<td>de Kok 1997</td>
</tr>
<tr>
<td>'baladica' subclade</td>
<td><em>Oxera aff. nuda</em></td>
<td>actinomorphic</td>
<td></td>
<td>rounded</td>
<td>paddle</td>
<td>40.6</td>
<td></td>
<td>de Kok 1997</td>
</tr>
<tr>
<td>'baladica' subclade</td>
<td><em>Oxera baladica</em></td>
<td>gullet</td>
<td></td>
<td>paddle</td>
<td></td>
<td>26.3</td>
<td></td>
<td>de Kok 1997, Fleurot pers.obs.</td>
</tr>
<tr>
<td>'baladica' subclade</td>
<td><em>Oxera doubetiae sp.nov.ined.</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>'baladica' subclade</td>
<td><em>Oxera garoensis sp.nov.ined.</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subclade</td>
<td>Species</td>
<td>Description</td>
<td>Flowers</td>
<td>References</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
<td>--------------------------------</td>
<td>-------------</td>
<td>---------</td>
<td>------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'baladica' subclade</td>
<td>Oxera oonemoeae sp.nov.ined.</td>
<td>thorny</td>
<td>30.6</td>
<td>de Kok 1997</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'baladica' subclade</td>
<td>Oxera papineau sp.nov.ined.</td>
<td>paddle</td>
<td>25.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'baladica' subclade</td>
<td>Oxera sessilifolia</td>
<td>thorny</td>
<td>40.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'baladica' subclade</td>
<td>Oxera vanuatuensis</td>
<td>paddle</td>
<td>35.0</td>
<td>de Kok 1997</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'neriifolia' subclade</td>
<td>Oxera neriifolia</td>
<td>bilabiate</td>
<td>rounded</td>
<td>de Kok 1997, Gateblé and Ouriet pers.obs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'neriifolia' subclade</td>
<td>Oxera ovata</td>
<td>bilabiate</td>
<td>rounded</td>
<td>Haxaire and Salesne (2016), de Kok 574 (in herb.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'neriifolia' subclade</td>
<td>Oxera sororia</td>
<td>rounded</td>
<td>13.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'oblongifolia' subclade</td>
<td>Oxera crassifolia</td>
<td>rounded</td>
<td>18.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'oblongifolia' subclade</td>
<td>Oxera glandulosa</td>
<td>rounded</td>
<td>11.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subclade</td>
<td>Species</td>
<td>Order</td>
<td>Gill Type</td>
<td>Rounded Diameter</td>
<td>Author(s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
<td>------------------------</td>
<td>----------------</td>
<td>------------</td>
<td>------------------</td>
<td>-----------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'oblongifolia'</td>
<td>Oxera oblongifolia</td>
<td>Lepidoptera</td>
<td>bilabiate</td>
<td>14.6</td>
<td>de Kok 568</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>subclade</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(in herb.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'oblongifolia'</td>
<td>Oxera oreophila</td>
<td>Lepidoptera</td>
<td>bilabiate</td>
<td>11.9</td>
<td>de Kok 1997</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>subclade</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxera morierei lineage</td>
<td>Oxera morierei</td>
<td>Honey eater</td>
<td>gullet</td>
<td>16.2</td>
<td>de Kok 1997</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Glycifohia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>undulata)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'pulchella' subclade</td>
<td>Oxera aff. balansae</td>
<td>Birds</td>
<td>gullet</td>
<td>12.2</td>
<td>de Kok 1997</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'pulchella' subclade</td>
<td>Oxera balansae</td>
<td>Honey eater</td>
<td>gullet</td>
<td>8.4</td>
<td>de Kok 1997,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Glycifohia</td>
<td></td>
<td></td>
<td>Desmoulins</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>undulata)</td>
<td></td>
<td></td>
<td>pers.obs.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'pulchella' subclade</td>
<td>Oxera brevicalyx</td>
<td>Honey eater</td>
<td>gullet</td>
<td>7.9</td>
<td>de Kok 1997,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Glycifohia</td>
<td></td>
<td></td>
<td>Desmoulins</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>undulata)</td>
<td></td>
<td></td>
<td>pers.obs.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'pulchella' subclade</td>
<td>Oxera pulchella</td>
<td>Honey eater</td>
<td>gullet</td>
<td>11.3</td>
<td>de Kok 1997</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Myzolema</td>
<td></td>
<td></td>
<td>Desmoulins</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>caledonica),</td>
<td></td>
<td></td>
<td>pers.obs.,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zosteropidae</td>
<td></td>
<td></td>
<td>Fleurot pers.obs.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Zosterops sp.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'robusta' subclade</td>
<td>Oxera coriacea</td>
<td>Honey eater</td>
<td>gullet</td>
<td>40.8</td>
<td>de Kok 1997</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Glycifohia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>undulata)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'robusta' subclade</td>
<td>Oxera coronata</td>
<td>Honey eater</td>
<td>gullet</td>
<td>29.9</td>
<td>de Kok 1997</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Lichmera</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'robusta' subclade</td>
<td>Oxera longifolia</td>
<td>Honey eater</td>
<td>gullet</td>
<td>37.2</td>
<td>de Kok 1997</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Lichmera</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'robusta' subclade</td>
<td>Oxera palmatinervia</td>
<td>Honey eater (Glycifohia undulata, Philemon diemenensis)</td>
<td>gullet</td>
<td>rounded 34.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------</td>
<td>--------------------------------------------------------</td>
<td>-------</td>
<td>------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'robusta' subclade</td>
<td>Oxera robusta</td>
<td>Honey eater (Philemon diemenensis)</td>
<td>gullet</td>
<td>paddle 40.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'subverticillata' subclade</td>
<td>Oxera subverticillata</td>
<td>Honey eater (Philemon diemenensis)</td>
<td>gullet</td>
<td>paddle 32.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'subverticillata' subclade</td>
<td>Oxera merytisfolia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'subverticillata' subclade</td>
<td>Oxera tiwaeanus sp.nov.ined.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'sulfurea' subclade</td>
<td>Oxera ouameniensis sp.nov.ined.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'sulfurea' subclade</td>
<td>Oxera microcalyx sp.nov.ined.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'sulfurea' subclade</td>
<td>Oxera pantheri</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'sulfurea' subclade</td>
<td>Oxera rugosa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Columbidae (Drepanoptila holosericea, Ducula Goliath)
deh Kok 1997, Bachy pers. obs., Desmoullins pers.obs.;
<table>
<thead>
<tr>
<th>'sulfurea' subclade</th>
<th>Oxera sulfurea</th>
<th>Honey eater (Lichmera incana, Myzomela caledonica, Glycifohia undulata)</th>
<th>gullet</th>
<th>Sturnidae (Aplonis striatus)</th>
<th>rounded</th>
<th>11.7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>[de Kok 1997, Desmoulin pers.obs., Gâteblé pers.obs.]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Comparison of net diversification rates of *Oxera* with other New Caledonian plant lineages / radiations. In grey, sclerophyllous clades.

<table>
<thead>
<tr>
<th>family</th>
<th>radiation</th>
<th>stem age (Ma)</th>
<th>crown age (Ma)</th>
<th>number of New Caledonian species retrieved from Muzinger et al. 2016</th>
<th>species number restricted to sclerophyll vegetation</th>
<th>species number able to growth in sclerophyll vegetation</th>
<th>proportion of species strictly growing in sclerophyll vegetation (%)</th>
<th>proportion of species able to grow in sclerophyll vegetation</th>
<th>net diversification rate (based on the equation of Magallón and Sanderson 2001) for an extinction null, and using crown ages (in species/Myr)</th>
<th>works where age estimates have been published</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sapotaceae</td>
<td><em>Planchonella</em> clade III</td>
<td>18</td>
<td>15</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>33.3</td>
<td>66.7</td>
<td>0.03</td>
<td>Swenson et al. 2013</td>
</tr>
<tr>
<td>Proteaceae</td>
<td><em>Beauprea</em> clade I ('filipes' clade)</td>
<td>78.2</td>
<td>28.3</td>
<td>7</td>
<td>1</td>
<td>5</td>
<td>14.3</td>
<td>71.4</td>
<td>0.04</td>
<td>He et al. 2016</td>
</tr>
<tr>
<td>Nothofagaceae</td>
<td><em>Nothofagus</em></td>
<td>26.1</td>
<td>16.4</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.06</td>
<td>Sauquet et al. 2012</td>
</tr>
<tr>
<td>Sapotaceae</td>
<td><em>Planchonella</em> clade I</td>
<td>15.3</td>
<td>12.05</td>
<td>4</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>75</td>
<td>0.06</td>
<td>Swenson et al. 2013</td>
</tr>
<tr>
<td>Proteaceae</td>
<td><em>Kermadecia</em> - <em>Sleumerodendron</em></td>
<td>13.6</td>
<td>12.3</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.07</td>
<td>Sauquet et al. 2009</td>
</tr>
<tr>
<td>Myrtaceae</td>
<td><em>Metrosideros</em> clade B</td>
<td>21.25</td>
<td>11</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td>20</td>
<td>60</td>
<td>0.08</td>
<td>Papadopoulos et al. 2011</td>
</tr>
<tr>
<td>Myrtaceae</td>
<td><em>Metrosideros</em> clade A</td>
<td>16.25</td>
<td>13.6</td>
<td>7</td>
<td>4</td>
<td>7</td>
<td>57.1</td>
<td>100</td>
<td>0.09</td>
<td>Papadopoulos et al. 2011</td>
</tr>
<tr>
<td>Areceaceae</td>
<td><em>Clinosperma</em> - <em>Cyphokentia</em></td>
<td>21.5</td>
<td>10.5</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
<td>Baker and Couvreur 2012</td>
</tr>
<tr>
<td>Myrtaceae</td>
<td><em>Metrosideros</em> clade C</td>
<td>29.1</td>
<td>8.25</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>40</td>
<td>80</td>
<td>0.11</td>
<td>Papadopoulos et al. 2011</td>
</tr>
<tr>
<td>Areceaceae</td>
<td><em>Chambevryonia</em> - <em>Kentaiopsis</em></td>
<td>9</td>
<td>4.5</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.12</td>
<td>Baker and Couvreur 2012</td>
</tr>
<tr>
<td>Sapotaceae</td>
<td><em>Pichonia</em></td>
<td>19</td>
<td>10.1</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>71.4</td>
<td>57.1</td>
<td>0.12</td>
<td>Swenson et al. 2013</td>
</tr>
<tr>
<td>Sapotaceae</td>
<td><em>Planchonella</em> clade II</td>
<td>33</td>
<td>17.4</td>
<td>18</td>
<td>7</td>
<td>7</td>
<td>38.9</td>
<td>38.9</td>
<td>0.13</td>
<td>Swenson et al. 2013</td>
</tr>
<tr>
<td>Rubiaceae</td>
<td><em>Margaritopsis</em></td>
<td>8.47</td>
<td>5.21</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>25</td>
<td>100</td>
<td>0.13</td>
<td>Barrabé et al. 2014</td>
</tr>
<tr>
<td>Rubiaceae</td>
<td><em>Psychotria</em> clade NC1</td>
<td>17.06</td>
<td>4.78</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>100</td>
<td>100</td>
<td>0.15</td>
<td>Barrabé et al. 2014</td>
</tr>
<tr>
<td>Class</td>
<td>Genus</td>
<td>clade</td>
<td>Length max 5.8</td>
<td>Length 5.8</td>
<td>Length 5</td>
<td>Length 5</td>
<td>Length 100</td>
<td>Length 100</td>
<td>Length 0.16</td>
<td>References</td>
</tr>
<tr>
<td>----------------</td>
<td>------------------</td>
<td>-------</td>
<td>----------------</td>
<td>------------</td>
<td>----------</td>
<td>----------</td>
<td>-------------</td>
<td>-------------</td>
<td>--------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Rutaceae</td>
<td>Oxanthera</td>
<td></td>
<td>10</td>
<td>4.9</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>40</td>
<td>Pfeil and Crips 2008</td>
</tr>
<tr>
<td>Sapotaceae</td>
<td>Pleioluma clade I</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>40</td>
<td>Swenson et al. 2013</td>
</tr>
<tr>
<td>Arecaceae</td>
<td>Burretiokentia - Cyphophoenix</td>
<td>11.5</td>
<td>7.5</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Baker and Couvreur 2012</td>
</tr>
<tr>
<td>Sapotaceae</td>
<td>Pycnandra</td>
<td></td>
<td>29.8</td>
<td>16.2</td>
<td>57</td>
<td>17</td>
<td>20</td>
<td>29.8</td>
<td>35.1</td>
<td>Swenson et al. 2013</td>
</tr>
<tr>
<td>Araucariaceae</td>
<td>Araucaria</td>
<td></td>
<td>16</td>
<td>8</td>
<td>13</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>53.8</td>
<td>Kranitz et al. 2014</td>
</tr>
<tr>
<td>Loganiaceae</td>
<td>Geniostoma</td>
<td></td>
<td>9</td>
<td>6.5</td>
<td>10</td>
<td>1</td>
<td>4</td>
<td>10</td>
<td>40</td>
<td>Foster et al. 2014</td>
</tr>
<tr>
<td>Podocarpaceae</td>
<td>Dacrydium</td>
<td></td>
<td>5</td>
<td>3.05</td>
<td>5</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>60</td>
<td>Keppel et al. 2011</td>
</tr>
<tr>
<td>Podocarpaceae</td>
<td>Podocarpus</td>
<td></td>
<td>6.9</td>
<td>4.2</td>
<td>8</td>
<td>2</td>
<td>2</td>
<td>25</td>
<td>25</td>
<td>Quiroga et al. 2016</td>
</tr>
<tr>
<td>Sapotaceae</td>
<td>Pleioluma clade II</td>
<td>7.5</td>
<td>4.2</td>
<td>8</td>
<td>6</td>
<td>8</td>
<td>75</td>
<td>100</td>
<td>0.33</td>
<td>Swenson et al. 2013</td>
</tr>
<tr>
<td>Anacardiaceae</td>
<td>Euroschinus</td>
<td></td>
<td>11.85</td>
<td>3.7</td>
<td>7</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>28.6</td>
<td>Weeks et al. 2014</td>
</tr>
<tr>
<td>Ebenaceae</td>
<td>Diospyros clade III</td>
<td>9.1</td>
<td>7.2</td>
<td>25</td>
<td>8</td>
<td>16</td>
<td>32</td>
<td>64</td>
<td>0.35</td>
<td>Turner et al. 2013</td>
</tr>
<tr>
<td>Pandanaceae</td>
<td>NC Pandanus subgen. Lophostigma</td>
<td>8.5</td>
<td>6.5</td>
<td>24</td>
<td>2</td>
<td>2</td>
<td>8.3</td>
<td>8.3</td>
<td>0.38</td>
<td>Gallaher et al. 2015</td>
</tr>
<tr>
<td>Ericaceae</td>
<td>Dracophyllum</td>
<td></td>
<td>5.2</td>
<td>3.5</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>87.5</td>
<td>75</td>
<td>Wagstaff et al. 2010</td>
</tr>
<tr>
<td>Rubiaceae</td>
<td>Psychotria clade NC2</td>
<td>7.63</td>
<td>6.9</td>
<td>78</td>
<td>32</td>
<td>40</td>
<td>41</td>
<td>51.3</td>
<td>0.53</td>
<td>Barrabé et al. 2014</td>
</tr>
<tr>
<td>Lamiaceae</td>
<td>NC Oxera</td>
<td></td>
<td>5.39</td>
<td>4.54</td>
<td>33</td>
<td>5</td>
<td>11</td>
<td>15.2</td>
<td>29.7</td>
<td>this study</td>
</tr>
<tr>
<td>Rubiaceae</td>
<td>Thiollierea</td>
<td></td>
<td>6.5</td>
<td>3</td>
<td>13</td>
<td>13</td>
<td>13</td>
<td>100</td>
<td>100</td>
<td>Manns et al. 2012</td>
</tr>
</tbody>
</table>
Table 3. Comparison of net diversification rates of Oxera with other rapid island plant lineages / radiations.

<table>
<thead>
<tr>
<th>Family</th>
<th>Radiation</th>
<th>archipelago</th>
<th>number of species</th>
<th>area (km²)</th>
<th>Median crown age (95% HPD in Ma)</th>
<th>net diversification rate and using crown ages (species/myr)</th>
<th>net diversification rate at a area unit (species/myr/km²)</th>
<th>net diversification rate at a log(area) unit (species/myr/log(km²))</th>
<th>works where age estimates and species number have been published</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamiaceae</td>
<td>New Caledonian Oxera</td>
<td>New Caledonia</td>
<td>33</td>
<td>18600</td>
<td>2.7</td>
<td>6.92</td>
<td>0.41-1.04</td>
<td>0.2-0.51</td>
<td>0.000011-0.000056</td>
</tr>
<tr>
<td>Rubiaceae</td>
<td>Psychotria clade NC2</td>
<td>New Caledonia</td>
<td>78</td>
<td>18600</td>
<td>4.62</td>
<td>9.82</td>
<td>0.37-0.79</td>
<td>0.22-0.46</td>
<td>0.000012-0.000043</td>
</tr>
<tr>
<td>Asteraceae</td>
<td>Cheilorophus</td>
<td>Macaronesia</td>
<td>20</td>
<td>10372</td>
<td>5.98</td>
<td>15.35</td>
<td>0.15-0.39</td>
<td>0.07-0.17</td>
<td>0.000006-0.000037</td>
</tr>
<tr>
<td>Euphorbiaceae</td>
<td>Euphorbia</td>
<td>Hawaii</td>
<td>16</td>
<td>16644</td>
<td>0.72</td>
<td>3.97</td>
<td>0.52-2.89</td>
<td>0.22-1.2</td>
<td>0.000013-0.000174</td>
</tr>
<tr>
<td>Asteraceae</td>
<td>Bidens</td>
<td>Hawaii</td>
<td>19</td>
<td>16644</td>
<td>1.3</td>
<td>3.1</td>
<td>0.73-1.73</td>
<td>0.32-0.75</td>
<td>0.000019-0.000104</td>
</tr>
<tr>
<td>Asteraceae</td>
<td>Echium</td>
<td>Macaronesia</td>
<td>19</td>
<td>10372</td>
<td>2.7</td>
<td>3.9</td>
<td>0.58-0.83</td>
<td>0.25-0.36</td>
<td>0.000024-0.00008</td>
</tr>
<tr>
<td>Gesneriaceae</td>
<td>Cyrtandra</td>
<td>Hawaii</td>
<td>58</td>
<td>16644</td>
<td>5.2</td>
<td>0.65</td>
<td>0.36</td>
<td>0.000021-0.000039</td>
<td>0.037-0.067</td>
</tr>
<tr>
<td>Campanulaceae</td>
<td>Lobeliads</td>
<td>Hawaii</td>
<td>126</td>
<td>16644</td>
<td>10.49</td>
<td>16.71</td>
<td>0.25-0.39</td>
<td>0.15-0.24</td>
<td>0.000009-0.000024</td>
</tr>
<tr>
<td>Crassulaceae</td>
<td>Aeonium</td>
<td>Macaronesia</td>
<td>63</td>
<td>10372</td>
<td>13.25</td>
<td>17.15</td>
<td>0.2-0.26</td>
<td>0.11-0.15</td>
<td>0.000011-0.000025</td>
</tr>
<tr>
<td>Plantaginaceae</td>
<td>Veronica</td>
<td>New Zealand</td>
<td>120</td>
<td>268680</td>
<td>5.7</td>
<td>0.72</td>
<td>0.44</td>
<td>0.000002-0.000003</td>
<td>0.035-0.057</td>
</tr>
</tbody>
</table>
Table 4. Combinations of ancestral node states (or character state for the single-species *morierei* lineage) of life forms, pollination and dispersal niches for each *Oxera* subclade, inferred from ancestral state reconstruction analyses. Numbers in brackets refer to tree node numbers in Figure 4. Clades with similar combinations are highlighted in grey.

<table>
<thead>
<tr>
<th>subclade / lineage</th>
<th>life form</th>
<th>pollination niche</th>
<th>dispersal niche</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>robusta</em> (1)</td>
<td>robust liana</td>
<td>gullet</td>
<td>large rounded</td>
</tr>
<tr>
<td><em>subverticillata</em> (2)</td>
<td>robust liana</td>
<td>gullet</td>
<td>paddle</td>
</tr>
<tr>
<td><em>sulfurea</em> (3)</td>
<td>shrub</td>
<td>gullet</td>
<td>small rounded</td>
</tr>
<tr>
<td><em>baladica</em> (4)</td>
<td>monocaulous</td>
<td>gullet</td>
<td>paddle</td>
</tr>
<tr>
<td><em>nerifolia</em> (5)</td>
<td>slender liana</td>
<td>bilabiate</td>
<td>small rounded</td>
</tr>
<tr>
<td><em>pulchella</em> (6)</td>
<td>slender liana</td>
<td>gullet</td>
<td>small rounded</td>
</tr>
<tr>
<td><em>oblongifolia</em> (7)</td>
<td>slender liana</td>
<td>bilabiate</td>
<td>small rounded</td>
</tr>
<tr>
<td><em>morierei</em> (8)</td>
<td>slender liana</td>
<td>gullet</td>
<td>small rounded</td>
</tr>
</tbody>
</table>
a) geographical overlap
- no overlap
- partial overlap
- entire overlap

habitat
- ubiquist
- ubiquist on UM
- ubiquist on NUM
- forest on UM
- forest on NUM
- sclerophyll vegetation

likely species coexistence

b) elevation (m)
- 0 500 1000 1500