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Applications in Plant Sciences

Applications in Plant Sciences 2017 5(3): 1600110

Genomic Resources Article

An *rbcL* reference library to aid in the identification of plant species mixtures by DNA metabarcoding[1]

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- *Premise of the study:* DNA metabarcoding has broad-ranging applications in ecology, aerobiology, biosecurity, and forensics. A bioinformatics pipeline has recently been published for identification using a comprehensive database of ITS2, one of the common plant DNA barcoding markers. There is, however, no corresponding database for *rbcL*, the other primary marker used in plants.
- *Methods:* Using publicly available data, we compiled a reference library of *rbcL* sequences and trained databases for use with UTAX and RDP classifier algorithms. We used this reference library, along with the existing bioinformatics pipeline and ITS2 reference library, to identify species in an artificial mixture of nine species of pollen. We have made this database publicly available in multiple formats, to allow use with multiple bioinformatics pipelines, now and in the future.
- *Results:* Using the *rbcL* database, in addition to the ITS2 database, we succeeded in making species-level identifications for eight species and a family-level identification of the ninth species. This is an improvement on ITS2 sequence alone.
- *Discussion:* The reference library described here will assist with identification of plant species using *rbcL*. By making another gene region available for standard barcoding, this will increase the resolution and accuracy of identifications.

Key words: DNA barcoding; DNA metabarcoding; plastid DNA; *rbcL*; species identification.

DNA metabarcoding, the use of high-throughput sequencing methods to simultaneously DNA barcode all species in a mixed sample, can been used to address a variety of questions in ecology, biosecurity, and forensics, among other fields (Cristescu, 2014; Bell et al., 2016a, 2016b). These methods enable taxonomic identifications of plant samples in which diagnostic characters are largely absent (e.g., roots in a soil sample, seeds from seed traps, or pollen), or for which few experts know the diagnostic characters. DNA metabarcoding has streamlined identifications of pollen for allergen monitoring (Kraaijeveld et al., 2015), plant-pollinator interactions (Keller et al., 2015; Richardson et al., 2015a, 2015b; Sickel et al., 2015; Pornon et al., 2016), and honey composition (Hawkins et al., 2015). The analysis of fragments of plant material in herbivore guts enables diet analysis (Valentini et al., 2009; Pompanon et al., 2012). DNA metabarcoding can also be used to determine the species composition of dietary supplements (Cheng et al., 2014) and foods (Hawkins et al., 2015) leading to improved health and safety. However, accurate determination of species by DNA metabarcoding is dependent on a comprehensive and accurate reference library of DNA sequences of a standard genetic marker, as well as an appropriate bioinformatics pipeline.

For plants, the Consortium for the Barcode of Life (CBOL) Plant Working group recommended the plastid DNA (ptDNA) genes *rbcL* and *matK* as standard DNA barcode markers, based on the availability of universal primers and the high level of taxonomic resolution (CBOL Plant Working Group, 2009; Hollingsworth et al., 2009). Recent studies using the standard *rbcL+matK* barcode for floras of moderate phylogenetic dispersion have shown that up to 92% of the species can be distinguished (Kress et al., 2009; Burgess et al., 2011). Amplicon fragment size is important in high-throughput sequencing (HTS) DNA metabarcoding, as the read lengths in many platforms are currently limited (e.g., ~600-bp paired-end reads on the Illumina MiSeq platform; Illumina, San Diego, California, USA). The long amplicon length generated by standard *matK* primers poses a technical limitation for these sequencing methods. In addition to ptDNA markers, the nuclear ribosomal spacer ITS2 has been shown to be an effective DNA barcoding marker, with 92.7% successful identifications in 6600 samples (Chen et al., 2010).

A bioinformatics pipeline has been published for the identification of species mixtures using ITS2 (Sickel et al., 2015). This bioinformatics pipeline was developed using dual-indexed mixed-amplicon sequence data from the Illumina MiSeq platform (adapting the method of Kozich et al., 2013), but can be used for any high-throughput sequencing platform that outputs data in FASTQ format. Sequencing reads are compared to

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a reference library of ITS2 sequences using two different programs—RDP classifier (Wang et al., 2007) and UTAX (Edgar, 2010). This pipeline currently cannot be used with either of the standard DNA barcode markers (*rbcL* or *matK*), due to the lack of reference libraries.

We report here on our development of reference libraries for taxonomic classification with RDP classifier and UTAX using *rbcL* sequences obtained from the National Center for Biotechnology Information (NCBI) database. We also made modifications to the bioinformatics pipeline of Sickel et al. (2015) to enable identifications from multiple markers amplified from the same sample, and these modifications could be applied to further additional barcodes, such as *matK* or *trnL*. We have used our *rbcL* reference libraries, along with existing ITS2 libraries and our modified bioinformatics pipeline, to classify sequences obtained from a constructed pollen sample composed of nine known species. We were able to successfully identify eight of the nine species using a combination of ITS2 and *rbcL*, where neither marker was sufficient for identification to the species level for more than six species on its own.

MATERIALS AND METHODS

***Developing the* rbcL *database*—**We selected *rbcL*, rather than *matK*, as our second DNA barcode, because the shorter PCR product allows for overlap of forward and reverse reads on the Illumina MiSeq. We downloaded all available seed plant *rbcL* sequences (as of 27 January 2016) from NCBI, using the following search: (rbcL[Gene Name] AND 50:400000000[Sequence Length]) AND "seed plants"[porgn:_txid58024]. This included sequences that were predominantly *rbcL*, sequences with a small fragment of *rbcL* sequence along with a longer sequence of intergenic spacer, and complete ptDNA genomes. We extracted the *rbcL* sequences from these records, using the "extract annotations" tool in Geneious version 7.1.9 (Biomatters, Auckland, New Zealand). We then filtered these extractions to remove any sequences of less than 100 bp. Previous studies have found interspecific sequence divergences of around 1–2% for *rbcL* (Hollingsworth et al., 2009; Kress and Erickson, 2007), so sequences of less than 100 bp would be unlikely to be informative. All sequences were exported as a single FASTA file from Geneious, with the "LOCUS" and "DEFINITION" fields from NCBI as the sequence header. We downloaded full details of each GenBank record, including the accession number and GenBank Identification (GI) number, from Geneious as a comma-separated value (.csv) file, prior to extraction of the *rbcL* annotated regions, because extraction with Geneious often causes this information to be lost, leaving only the "LOCUS" field to determine the origin of the sequence. We used R (R Core Team, 2016) scripts to replace the "LOCUS" field information from the sequence headers of the FASTA file with the GI number, accession number, and species for each sequence. We included both identifiers (rather than GI only) to be compatible with future bioinformatics pipelines, following the phasing out of GI numbers by NCBI in September 2016. Reference databases for RDP classifier and UTAX were built from the *rbcL* sequences using the method described in Sickel et al. (2015) for training of the ITS2 databases; these were then deposited on Figshare, along with the FASTA file described above (https://dx.doi.org/10.6084/m9.figshare.c.3466311). The FASTA file can be used to develop reference libraries for other classification programs, if desired.

***Adapting existing bioinformatics pipeline*—**We accessed the bioinformatics pipeline of Sickel et al. (2015) through their website at https://github.com/iimog/meta-barcoding-dual-indexing, along with instructions for installing all of the required programs. Their bioinformatics pipeline includes commands for joining forward and reverse reads using QIIME version 1.8.0 (Caporaso et al., 2010), removing low-quality reads with USEARCH version 8.0.1477 (Edgar, 2010), and taxonomic classification of the remaining high-quality sequences using RDP classifier (Wang et al., 2007) and/or UTAX (Edgar, 2010). Although there are other algorithms for matching sequences (e.g., BLAST), algorithms like RDP and UTAX are faster because they cluster sequences before searching them against the databases, and they give more robust results as they consider the taxonomic hierarchy, rather than just returning the best hit.

The pipeline of Sickel et al. (2015) has been designed to be run with their database of ITS2 sequences (Ankenbrand et al., 2015), but can easily be run with other databases, provided the sequences are available. Once the pipeline has been run in its entirety, it is not necessary to run the entire pipeline to compare the joined and filtered FASTQ files against a second, or further, database of sequences. We removed the lines associated with joining and filtering FASTQ files from the script 'classify_reads.pl' of Sickel et al. (2015) to allow the FASTQ files that were joined and filtered before searching against the first database (in this case, ITS2) using the full bioinformatics pipeline, to be compared to other databases (in this case, *rbcL* sequences). We have called this script 'classify_reads_subsequent.pl' and made it available from https://github.com/KarenBell/rbcL-dual-index-metabarcoding. The basic workflow of the modified bioinformatics pipeline, assuming analysis with ITS2 followed by analysis with *rbcL*, is depicted in Fig. 1.

***Testing the database*—**We tested the newly developed *rbcL* database, in combination with the existing ITS2 database, using sequencing data from an artificial pollen sample composed of nine taxonomically diverse angiosperm species: *Populus tremuloides* Michx. (Salicaceae) (Sigma-Aldrich Co., St. Louis, Missouri, USA), *Populus deltoides* W. Bartram ex Marshall (Sigma-Aldrich Co.), *Broussonetia papyrifera* (L.) Vent. (Moraceae) (Polysciences, Warrington, Pennsylvania, USA), *Carya illinoinensis* (Wangenh.) K. Koch (Juglandaceae) (Polysciences), *Bassia scoparia* (L.) A. J. Scott (Amaranthaceae) (Sigma-Aldrich Co.), *Ambrosia artemisiifolia* L. (Asteraceae) (Polysciences), *Artemisia tridentata* Nutt. (Asteraceae) (Sigma-Aldrich Co.), *Poa pratensis* L. (Poaceae) (Sigma-Aldrich Co.), and *Zea mays* L. (Poaceae) (Carolina Biological Supply, Burlington, North Carolina, USA). These species were selected because they were available commercially and cover a broad range of plant taxonomic diversity. We suspended pollen of each species in a mixture of 1:3 glycerol:ethanol and estimated the concentration of pollen grains in these suspensions through microscopic examination. We added an appropriate volume of each suspension to make a mixture containing similar numbers of pollen grains from each species and a total of 1,000,000 pollen grains. We determined the actual composition of this mixture by examining four replicate microscope slides of approximately 200 pollen grains from each mixture using Classifynder, an automated pollen identification and counting system (Holt et al., 2011). We tested for any bias in the Classifynder identification and counting through visual examination of one slide by three different individuals, comparing these counts to the automated counts.

We isolated DNA from the constructed pollen mixture, and a negative control, using the FastDNA SPIN Kit for Soil (MP Biomedicals, Solon, Ohio, USA), with the following modifications: 150 µL 10% sodium dodecyl sulfate (SDS) (Promega Corporation, Madison, Wisconsin, USA) and 20 µL 10 mg/mL Proteinase K (QIAGEN, Valencia, California, USA) were added to the sample along with the MT Buffer; homogenization was conducted using a mini-bead beater (Biospec Products, Bartlesville, Oklahoma, USA) for 3 min, followed by incubation for 30 min at 55°C, followed by a further 3 min in the mini-bead beater (preliminary analysis of three different species showed that this was sufficient to rupture the majority of pollen grains); and DNA was eluted in 80 µL DES (DNase/pyrogen-free water), with a 5-min incubation at 55°C.

We amplified the *rbcL* and ITS2 markers in separate reactions using a modification of methods developed for mixed-amplicon sequencing of bacterial 16S (Kozich et al., 2013). Primers for the first round of PCR were standard DNA barcoding primers with Illumina overhang sequences appended (Kozich et al., 2013). For *rbcL* we used the primers rbcL2, which binds near the 5′ end of the *rbcL* gene (Palmieri et al., 2009), and rbcLa-R, which binds near the middle of the *rbcL* gene (Kress and Erickson, 2007), which yield a PCR product of ~500 bp. For ITS2 we used the primers ITS2 S2F and ITS2 S3R, which bind to 5.8S and near the 3′ end of ITS2, respectively, and yield a PCR product of 350–400 bp (Chen et al., 2010). PCR reactions contained KAPA HiFi HotStart ReadyMix (KAPA Biosystems, Boston, Massachusetts, USA), each primer at a final concentration of 200 nM, and 12 µL of a 1/5 dilution of DNA isolate (43 ng total DNA) in a total volume of 25 µL. PCR cycles included an initial heat activation for 3 min at 95°C; followed by 30 cycles of 30 s at 95°C, 30 s at 55°C, and 50 s at 72°C; followed by a final extension of 7 min at 72°C. The PCR was conducted in triplicate. In addition to the negative control from the DNA isolation step, we included a PCR negative control (water only). We prepared indexed Illumina MiSeq libraries from these PCR products using a limited cycle PCR, adding Illumina sequencing adapters and Nextera XT dual-index barcodes (Illumina). We used different index combinations for each triplicate and negative control, with the same index being used for *rbcL* and ITS2 for the same sample (five index combinations and 10 PCR reactions in total). We purified the PCR products

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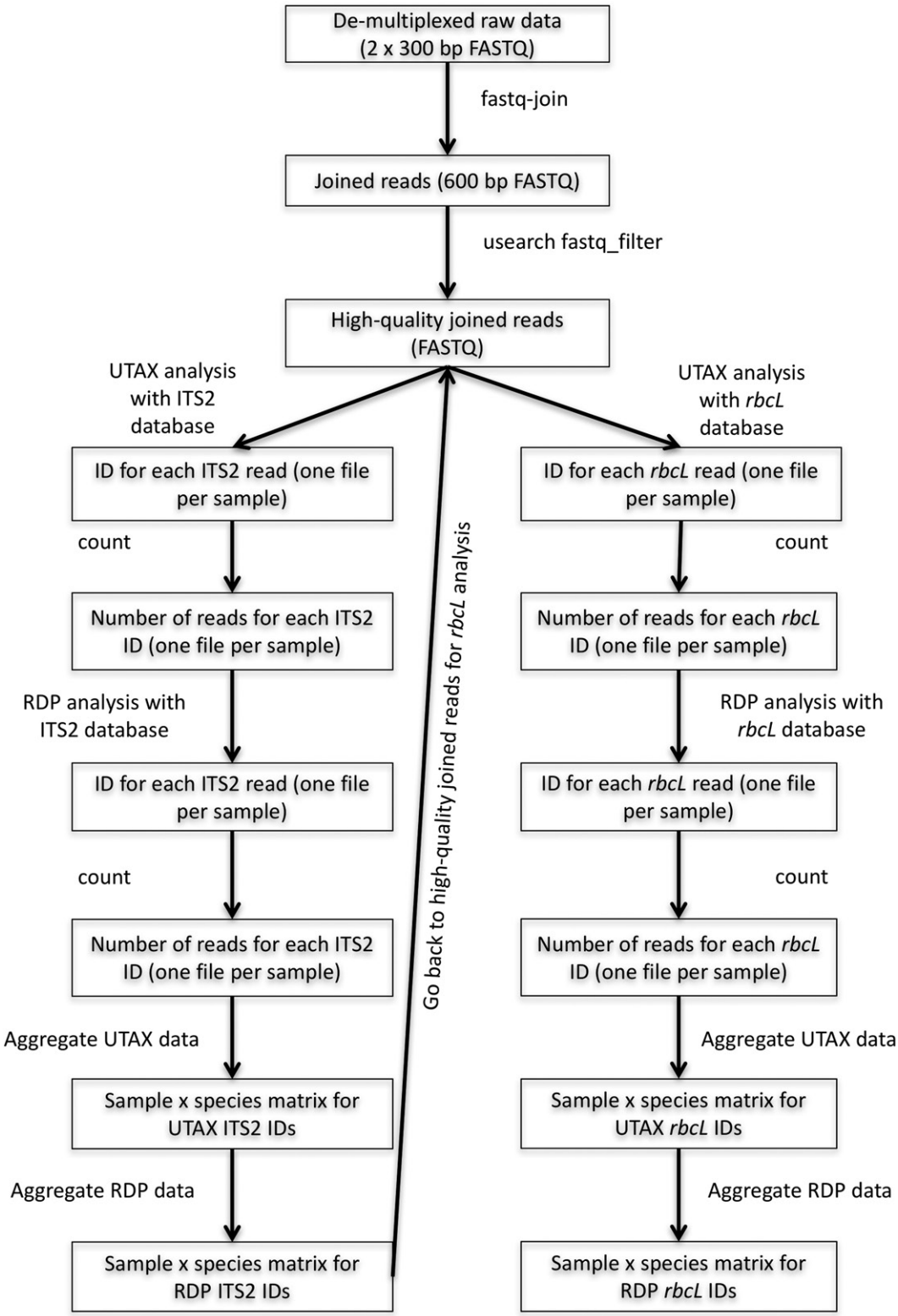


Fig. 1. Flow chart of modified bioinformatics pipeline, including ITS2 and *rbcL* analysis.

using Agencourt AMPure XP magnetic beads (Beckman Coulter, Danvers, Massachusetts, USA), and the DNA was quantified at the Emory Integrated Genomics Core (EIGC) using the Bioanalyzer instrument (Agilent Technologies, Santa Clara, California, USA). The PCR reactions were multiplexed with other samples, allocating each PCR reaction 1/192 of the total DNA content on a single flow cell (i.e., allocating each sample 1/96 of the total DNA once *rbcL* and ITS2 PCR are combined), except for negative controls that were multiplexed at the same volume as the most dilute sample (i.e., the maximum volume added).

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Sequencing was conducted by the EIGC, with a 2 × 300 bp run of the Illumina MiSeq instrument.

We used the bioinformatics pipeline of Sickel et al. (2015) to classify ITS2 reads. We then used our modified Perl script and our databases to classify *rbcL* reads. After classification, we removed any identifications occurring at a lower frequency than identifications obtained in either negative control. We compared classification success of ITS2 alone, *rbcL* alone, and both markers combined, using the RDP and UTAX classification methods. Success was defined in terms of correct identification to any taxonomic level, correct identification to species level, and incorrect identifications.

When we were unable to detect a species with either ITS2 or *rbcL*, we checked for sequences in the NCBI database that might be able to identify the species (e.g., if the sequences were not identified as ITS2 or *rbcL* in the NCBI database). We selected one of our three triplicate samples, compared the first 1000 sequences against the entire NCBI database using a BLAST search, and checked for matches to any species that had not been identified using the method described in the previous paragraphs.

RESULTS

***The* rbcL *database*—**We successfully developed a database containing *rbcL* sequences from 38,409 seed plant species. This compares to 72,325 species in the ITS2 database (Sickel et al., 2015) and an estimated 450,000 flowering plant species on earth (Pimm and Joppa, 2015). For the species included in our artificial pollen mixture, most were represented by multiple sequences, many vouchered. For most species, vouchered congeneric sequences were also available, although sometimes only for a small proportion of the total diversity of the genus (Table 1). The majority of sequences were in the length range of 501–1000 bp (Fig. 2). This category would include typical DNA barcode sequences, which are 600 bp for the most commonly used primer pair (Kress and Erickson, 2007). Full-length *rbcL* sequences are around 2500 bp in length and only represent a small portion of the sequences in our database.

***Testing the database*—**Our three technical replicates produced 85,378, 38,398, and 74,843 sequencing reads, giving a total of 198,619 sequencing reads. Analysis with RDP identified 65,639 of these reads as ITS2 and 130,320 as *rbcL*, leaving 2660 unclassified. Analysis with UTAX identified 67,149 ITS2 reads, 131,260 *rbcL* reads, with 210 unclassified reads. Our isolation negative control contained 34 sequencing reads, while our PCR negative control contained 30 sequencing reads.

In most cases, taxonomic assignments were able to identify all nine species present in the mixture, although certain species were missed in some analyses, either due to low numbers of reads or absence in reference libraries (Table 2). Similar results were obtained with the same analysis method for each triplicate PCR (Table 3). Based on ITS2 analysis alone, we were unable to detect *Artemisia tridentata* or *Populus tremuloides*. In both cases, a closely related species was detected, *A. keiskeana* Miq. and *P. alba* L., respectively. *Populus tremuloides* is not represented in the ITS2 reference library. *Zea mays* could be detected, but with fewer reads than our false-positive threshold (i.e., fewer than the number of reads obtained in negative controls). Based on *rbcL* analysis alone, we were unable to detect *Carya illinoinensis*. Instead, *C. illinoinensis* was identified as *Juglans regia* L. or *Pterocarya stenoptera* C. DC., or the reads were identified correctly to family level. *Ambrosia artemisiifolia* was detected from only a small number of reads (below the contamination threshold) with *rbcL*, while *Artemisia tridentata* was entirely undetected, due to its absence in the *rbcL* reference library. The only species that could not be detected above the contamination threshold with at least one marker was *A. tridentata*. A BLAST search of our first 1000 sequence reads against the NCBI database (accessed 28–29 November 2016), saving the 10 best matches for each search, included identifications of *A. tridentata* ITS2, but these identifications were never the single highest score. No sequencing reads were identified as *A. tridentata rbcL.* A BLAST search of the complete data set of 198,619 sequences against the entire NCBI database was not feasible.

Analysis with RDP identified sequences in the isolation negative control as *Ambrosia artemisiifolia* ITS2 (5 sequences), Asteraceae *rbcL* (4 sequences), *Populus rbcL* (2 sequences), Poaceae *rbcL* (1 sequence), and *Broussonetia papyrifera rbcL* (1 sequence), while 21 sequences could not be identified with *rbcL* or ITS2. Analysis with UTAX identified *Ambrosia artemisiifolia* ITS2 (5 sequences), *Artemisia maritima* L. *rbcL* (3 sequences), *Populus tremuloides rbcL* (2 sequences), *Poa pratensis* ITS2 (2 sequences), *Artemisia keiskeana* ITS2 (2 sequences), *Zea mays rbcL* (1 sequence), *Artemisia frigida* Willd. *rbcL* (1 sequence), *B. papyrifera rbcL* (1 sequence), *Ambrosia trifida* L. ITS2 (1 sequence), and *Xanthium sibiricum* Patrin ex Widder ITS2 (1 sequence), with 15 unidentified. Taxonomic identifications from RDP analysis of the 30 sequences in the PCR negative controls were *Ambrosia artemisiifolia* ITS2 (8 sequences), Poaceae *rbcL* (3 sequences), Asteraceae *rbcL*

TABLE 1. Sequence representation on NCBI of the nine species used for testing our *rbcL* reference library, and congeneric species.

Species	No. of *rbcL* sequences	No. of vouchered *rbcL* sequences[a]	No. of species in genus[b]	No. of congeneric species with *rbcL* sequences	No. of congeneric species with vouchered *rbcL* sequences[a]
Populus deltoides	10	6	174	46	28
Populus tremuloides	14	7	174	46	28
Broussonetia papyrifera	15	11	31	2	0
Carya illinoinensis	2	1	47	10	6
Bassia scoparia	3	1	217	5	2
Ambrosia artemisiifolia	9	9	76	3	1
Artemisia tridentata	0	0	870	27	16
Poa pratensis	62	45	1613	94	93
Zea mays	13	0	32	0	0

[a]A sequence is considered to be vouchered if the word "voucher" was found in the NCBI record. Further sequences may be associated with vouchers that are not included in the NCBI record, but are recorded in the associated publication.

[b]Information obtained from the Tropicos online database (Missouri Botanical Garden, 2016). Species names that were invalid or illegitimate were excluded.

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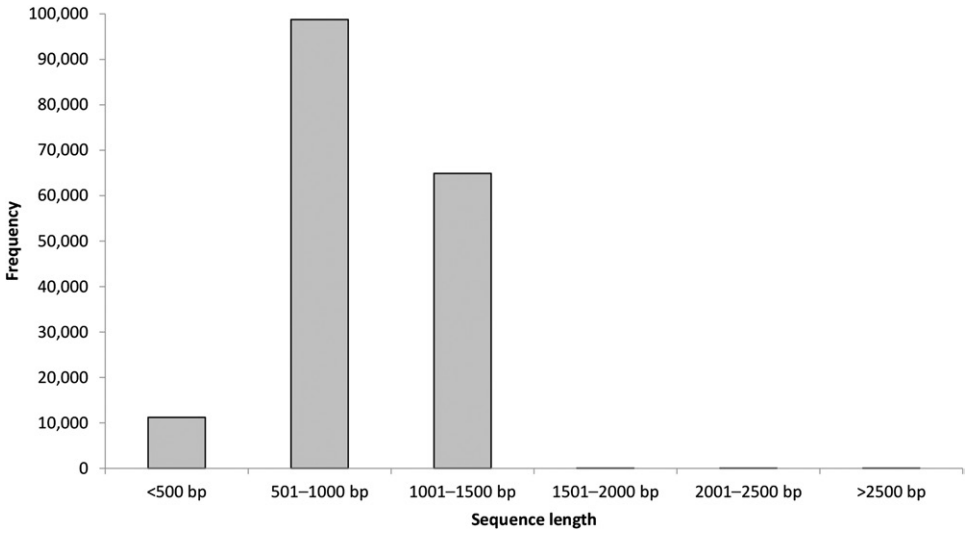


Fig. 2. Lengths of *rbcL* sequences present in our database.

(3 sequences), *Poa pratensis rbcL* (2 sequences), *Populus rbcL* (2 sequences), *Ambrosia rbcL* (1 sequence), *Artemisia annua* L. *rbcL* (1 sequence), rosid *rbcL* (1 sequence), *Populus deltoides rbcL* (1 sequence), Rosales *rbcL* (1 sequence), *Bassia scoparia rbcL* (1 sequence), and *B. scoparia* ITS2 (1 sequence), with five sequences unidentified. Taxonomic identifications from the UTAX analysis were *Ambrosia artemisiifolia* ITS2 (8 sequences), *Populus tremuloides rbcL* (3 sequences), *Holcus lanatus* L. *rbcL* (2 sequences), *Artemisia frigida rbcL* (2 sequences), *Artemisia maritima rbcL* (2 sequences), *Festuca subverticillata* (Pers.) E. B. Alexeev *rbcL* (1 sequence), *Vulpia unilateralis* (L.) Stace *rbcL* (1 sequence), *Poa pratensis rbcL* (1 sequence), *Ambrosia artemisiifolia rbcL* (1 sequence), *Broussonetia papyrifera rbcL* (1 sequence), *Bassia scoparia rbcL* (1 sequence), and *B. scoparia* ITS2 (1 sequence), with six sequences unidentified.

DISCUSSION

In this study, we have developed an *rbcL* reference sequence database and incorporated this into an existing ITS2 bioinformatics pipeline. By formatting the reference libraries for use with an existing bioinformatics pipeline, we have allowed for a streamlined analysis of sequencing data containing both ITS2 and *rbcL* reads. We have also allowed for improved standardization across studies, by developing a database for one of the two standard DNA barcoding markers (CBOL Plant Working Group, 2009). By combining these two markers, we were able to achieve more accurate species-level identifications than using ITS2 alone. The combination of ITS2 and *rbcL* sequence data enabled us to identify to species level eight of nine plant species in a mixture, and we were able to detect all genera. This compares to only six species-level identifications based on ITS2 only. We obtained fewer high-quality sequence reads from *rbcL* than ITS2. This may be because the *rbcL* fragment is longer, with less overlap between forward and reverse reads, causing more reads to be removed during filtering. If it were strongly desirable to have equal numbers of high-quality sequences from both markers, this could be corrected by adding more *rbcL* PCR products at the pooling step before MiSeq analysis.

The most common explanations for misidentifications were the absence of the species in the reference library or the lack of species-level variation in sequences. While our reference library represents a significant advance in plant DNA metabarcoding, our *rbcL* reference library and the ITS2 reference library of Sickel et al. (2015) fall far short of being comprehensive. There are an estimated 450,000 flowering plant species on earth (Pimm

Table 2. Summary of identification success, based on analysis of ITS2 and *rbcL* sequence data, using RDP and UTAX, for a nine-species mixture.

	RDP			UTAX		
Species	ITS2	*rbcL*	Both	ITS2	*rbcL*	Both
Ambrosia artemisiifolia	Species	Family	Species	Species	Undetected	Species
Artemisia tridentata	Misidentified	Family	Family	Misidentified	Misidentified	Misidentified
Bassia scoparia	Species	Species	Species	Species	Species	Species
Broussonetia papyrifera	Species	Species	Species	Species	Species	Species
Carya illinoinensis	Species	Undetected	Species	Species	Family	Species
Poa pratensis	Species	Species	Species	Species	Species	Species
Populus deltoides	Species	Species	Species	Species	Species	Species
Populus tremuloides	Misidentified	Species	Species	Misidentified	Species	Species
Zea mays	Undetected	Misidentified	Misidentified	Undetected	Species	Species

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TABLE 3. Proportion of total sequencing reads identified as *rbcL* or ITS2 of each of nine focal species in three replicate sequencing reactions of a constructed pollen mixture, analyzed with RDP and UTAX.

	rbcL analyzed with RDP			*rbcL* analyzed with UTAX			ITS2 analyzed with RDP			ITS2 analyzed with UTAX		
Species	1	2	3	1	2	3	1	2	3	1	2	3
Populus deltoides proportion	0.021	0.022	0.023	0.101	0.078	0.102	0.0032	0.0041	0.0026	0.0035	0.0041	0.0029
Populus tremuloides proportion	0.0011	0.0008	0.0010	0.39	0.32	0.39	0	0	0	0	0	0
Broussonetia papyrifera proportion	0.036	0.026	0.032	0.065	0.054	0.060	0.0006	0.0008	0.0006	0.0002	0.0003	0.0003
Carya illinoinensis proportion	0	0	0	0	0	0	0.0004	0.0009	0.0006	0.0002	0.0003	0.0003
Bassia scoparia proportion	0.011	0.011	0.011	0.012	0.012	0.012	0.023	0.032	0.024	0.029	0.039	0.031
Ambrosia artemisiifolia proportion	0	0	0	0	0.00003	0.00003	0.090	0.126	0.095	0.067	0.103	0.071
Artemisia tridentata proportion	0	0	0	0	0	0	0	0	0	0	0.00003	0
Poa pratensis proportion	0.029	0.025	0.027	0.025	0.021	0.023	0.024	0.037	0.026	0.042	0.058	0.040
Zea mays proportion	0	0	0	0.0071	0.0061	0.0057	0.00006	0.00008	0	0.00007	0.00001	0.00004

and Joppa, 2015). Our databases represent 10–20% of this biodiversity. Furthermore, many online data repositories, such as the International Nucleotide Sequences Database Collaboration (http://www.ncbi.nlm.nih.gov/genbank/collab), which incorporates GenBank (Benson et al., 2015), the DNA Data Bank of Japan (DDBJ; Mashima et al., 2015), and the European Molecular Biology Laboratory (EMBL) Nucleotide Sequence Database (Squizzato et al., 2015), do not require researchers submitting sequences to provide links to voucher specimens or raw sequence data, and may include sequences with incorrect species identification or low-quality sequence data. Other databases, such as the Barcode of Life Database (BOLD; Ratnasingham and Hebert, 2007), have stringent quality control but fewer plant *rbcL* sequences than the NCBI database, and no plant ITS2 sequences. As online databases become populated with more species, particularly those such as BOLD that have stringent quality control, these sequences can be added to our *rbcL* database, providing more comprehensive and accurate reference libraries for DNA metabarcoding analyses, which will lead to improvements in species-level identifications.

A lack of species-level variation was also found to hinder species-level identifications, particularly when only considering data from ITS2 or *rbcL* individually. This was likely the case with *Artemisia tridentata* being identified as *A. keiskeana*. Using ITS2 and *rbcL* in combination, most species in the mixtures could be identified. By providing a reference library for *rbcL*, we have improved identification accuracy by allowing identification from multiple markers. When DNA metabarcoding a sample of unknown species composition, conflicting results from different loci or different analysis methods (e.g., the different results for *Populus tremuloides* from *rbcL* or ITS2 sequences) may be difficult to resolve. In these situations, it may be necessary to resolve the taxonomic identification at a higher rank (e.g., a genus-level identification of *Populus*). Adding a third marker, such as *matK* or *trnL*, may also help here.

Two of the species we examined, *Zea mays* and *Ambrosia artemisiifolia*, were undetected above the contamination threshold with one of the two barcodes (ITS2 and *rbcL*, respectively), rather than misidentified. This is not due to poor DNA isolation for these species, as they were both detected with the other marker. This is probably best explained by amplification bias, where certain species are less readily amplified under the combination of primers and PCR conditions, or copy number bias, where the markers are present in lower copy numbers in the genomes of some species. This emphasizes the importance of using multiple unlinked markers in DNA metabarcoding studies.

Increasing the accuracy of DNA barcoding and metabarcoding will advance research across a range of disciplines. DNA metabarcoding methods enable taxonomic identifications of mixed-species plant samples in which diagnostic characters may be absent, including pollen (Bell et al., 2016b), herbivore gut contents (Valentini et al., 2009; Pompanon et al., 2012), and traditional medicines (Cheng et al., 2014). All of these identifications are dependent on comprehensive and accurate reference libraries of DNA sequences of standard genetic markers, such as the *rbcL* library of the current study. In the future, as similar databases become available for other molecular markers, such as *matK* or *trnL*, this will allow for even greater accuracy of taxonomic classification by DNA metabarcoding, and subsequent advancement in a multitude of fields of research.

LITERATURE CITED

ANKENBRAND, M. J., A. KELLER, M. WOLF, J. SCHULTZ, AND F. FÖRSTER. 2015. ITS2 database V: Twice as much. *Molecular Biology and Evolution* 32: 3030–3032.

BELL, K. L., K. S. BURGESS, K. C. OKAMOTO, R. ARANDA, AND B. J. BROSI. 2016a. Review and future prospects for DNA barcoding methods in forensic palynology. *Forensic Science International: Genetics* 21: 110–116.

BELL, K. L., N. DE VERE, A. KELLER, R. T. RICHARDSON, A. GOUS, K. S. BURGESS, AND B. J. BROSI. 2016b. Pollen DNA barcoding: Current applications and future prospects. *Genome* 59: 629–640.

BENSON, D. A., K. CLARK, I. KARSCH-MIZRACHI, D. J. LIPMAN, J. OSTELL, AND E. W. SAYERS. 2015. GenBank. *Nucleic Acids Research* 43: D30–D35.

BURGESS, K. S., A. J. FAZEKAS, P. R. KESANAKURTI, S. W. GRAHAM, B. C. HUSBAND, S. G. NEWMASTER, D. M. PERCY, ET AL. 2011. Discriminating plant species in a local temperate flora using the *rbcL* + *matK* DNA barcode. *Methods in Ecology and Evolution* 2: 333–340.

CAPORASO, J. G., J. KUCZYNSKI, J. STOMBAUGH, K. BITTINGER, F. D. BUSHMAN, E. K. COSTELLO, N. FIERER, ET AL. 2010. QIIME allows analysis of high-throughput community sequencing data. *Nature Methods* 7: 335–336.

CBOL PLANT WORKING GROUP. 2009. A DNA barcode for land plants. *Proceedings of the National Academy of Sciences, USA* 106: 12794–12797.

CHEN, S., H. YAO, J. HAN, C. LIU, J. SONG, L. SHI, Y. ZHU, ET AL. 2010. Validation of the ITS2 region as a novel DNA barcode for identifying medicinal plant species. *PLoS ONE* 5: e8613.

CHENG, X., X. SU, X. CHEN, H. ZHAO, C. BO, J. XU, H. BAI, AND K. NING. 2014. Biological ingredient analysis of traditional Chinese medicine preparation based on high-throughput sequencing: The story for Liuwei Dihuang Wan. *Scientific Reports* 4: 5147.

CRISTESCU, M. E. 2014. From barcoding single individuals to metabarcoding biological communities: Towards an integrative approach to the study of global biodiversity. *Trends in Ecology & Evolution* 29: 566–571.

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Edgar, R. C. 2010. Search and clustering orders of magnitude faster than BLAST. *Bioinformatics (Oxford, England)* 26: 2460–2461.

Hawkins, J., N. de Vere, A. Griffith, C. R. Ford, J. Allainguillaume, M. J. Hegarty, L. Baillie, and B. Adams-Groom. 2015. Using DNA metabarcoding to identify the floral composition of honey: A new tool for investigating honey bee foraging preferences. *PLoS ONE* 10: e0134735.

Hollingsworth, M. L., A. A. Clark, L. L. Forrest, J. Richardson, R. T. Pennington, D. G. Long, R. S. Cowan, et al. 2009. Selecting barcoding loci for plants: Evaluation of seven candidate loci with species-level sampling in three divergent groups of land plants. *Molecular Ecology Resources* 9: 439–457.

Holt, K., G. Allen, R. Hodgson, S. Marsland, and J. Flenley. 2011. Progress towards an automated trainable pollen location and classifier system for use in the palynology laboratory. *Review of Palaeobotany and Palynology* 167: 175–183.

Keller, A., N. Danner, G. Grimmer, M. Ankenbrand, K. von der Ohe, W. von der Ohe, S. Rost, et al. 2015. Evaluating multiplexed next-generation sequencing as a method in palynology for mixed pollen samples. *Plant Biology* 17: 558–566.

Kozich, J. J., S. L. Westcott, N. T. Baxter, S. K. Highlander, and P. D. Schloss. 2013. Development of a dual-index sequencing strategy and curation pipeline for analyzing amplicon sequence data on the MiSeq Illumina sequencing platform. *Applied and Environmental Microbiology* 79: 5112–5120.

Kraaijeveld, K., L. A. de Weger, M. Ventayol García, H. Buermans, J. Frank, P. S. Hiemstra, and J. T. den Dunnen. 2015. Efficient and sensitive identification and quantification of airborne pollen using next-generation DNA sequencing. *Molecular Ecology Resources* 15: 8–16.

Kress, W. J., and D. L. Erickson. 2007. A two-locus global DNA barcode for land plants: The coding *rbcL* gene complements the non-coding *trnH-psbA* spacer region. *PLoS ONE* 2: e508.

Kress, W. J., D. L. Erickson, F. A. Jones, N. G. Swenson, R. Perez, O. Sanjur, and E. Bermingham. 2009. Plant DNA barcodes and a community phylogeny of a tropical forest dynamics plot in Panama. *Proceedings of the National Academy of Sciences, USA* 106: 18621–18626.

Mashima, J., Y. Kodama, T. Kosuge, T. Fujisawa, T. Katayama, H. Nagasaki, Y. Okuda, et al. 2015. DNA data bank of Japan (DDBJ) progress report. *Nucleic Acids Research* 44: D51–D57.

Missouri Botanical Garden. 2016. Tropicos.org. Website http://www.tropicos.org [accessed 7 December 2016].

Palmieri, L., E. Bozza, and L. Giongo. 2009. Soft fruit traceability in food matrices using real-time PCR. *Nutrients* 1: 316–328.

Pimm, S. L., and L. N. Joppa. 2015. How many plant species are there, where are they, and at what rate are they going extinct? *Annals of the Missouri Botanical Garden* 100: 170–176.

Pompanon, F., B. E. Deagle, W. O. C. Symondson, D. S. Brown, S. N. Jarman, and P. Taberlet. 2012. Who is eating what: Diet assessment using next generation sequencing. *Molecular Ecology* 21: 1931–1950.

Pornon, A., N. Escaravage, M. Burrus, H. Holota, A. Khimoun, J. Mariette, C. Pellizzari, et al. 2016. Using metabarcoding to reveal and quantify plant-pollinator interactions. *Scientific Reports* 6: 27282.

R Core Team. 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ratnasingham, S., and P. D. N. Hebert. 2007. BOLD: The Barcode of Life Data System (http://www.barcodinglife.org). *Molecular Ecology Notes* 7: 355–364.

Richardson, R. T., C.-H. Lin, J. O. Quijia, N. S. Riusech, K. Goodell, and R. M. Johnson. 2015a. Rank-based characterization of pollen assemblages collected by honey bees using a multi-locus metabarcoding approach. *Applications in Plant Sciences* 3: 1500043.

Richardson, R. T., C.-H. Lin, D. B. Sponsler, J. O. Quijia, K. Goodell, and R. M. Johnson. 2015b. Application of ITS2 metabarcoding to determine the provenance of pollen collected by honey bees in an agroecosystem. *Applications in Plant Sciences* 3: 1400066.

Sickel, W., M. J. Ankenbrand, G. Grimmer, A. Holzschuh, S. Härtel, J. Lanzen, I. Steffan-Dewenter, and A. Keller. 2015. Increased efficiency in identifying mixed pollen samples by meta-barcoding with a dual-indexing approach. *BMC Ecology* 15: 20.

Squizzato, S., Y. M. Park, N. Buso, T. Gur, A. Cowley, W. Li, M. Uludag, et al. 2015. The EBI Search engine: Providing search and retrieval functionality for biological data from EMBL-EBI. *Nucleic Acids Research* 43: W585–W588.

Valentini, A., C. Miquel, M. A. Nawaz, E. Bellemain, E. Coissac, F. Pompanon, L. Gielly, et al. 2009. New perspectives in diet analysis based on DNA barcoding and parallel pyrosequencing: The *trnL* approach. *Molecular Ecology Resources* 9: 51–60.

Wang, Q., G. M. Garrity, J. M. Tiedje, and J. R. Cole. 2007. Naive Bayesian classifier for rapid assignment of rRNA sequences into the new bacterial taxonomy. *Applied and Environmental Microbiology* 73: 5261–5267.

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