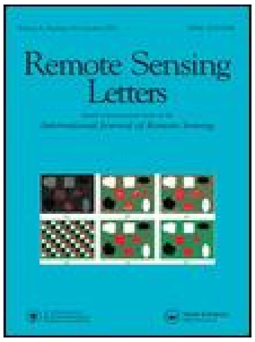

Remote Sensing Letters

ISSN: 2150-704X (Print) 2150-7058 (Online) Journal homepage: http://www.tandfonline.com/loi/trsl20

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To cite this article: Chunyuan Diao & Le Wang (2016) Temporal partial unmixing of exotic salt cedar using Landsat time series, Remote Sensing Letters, 7:5, 466-475, DOI: 10.1080/2150704X.2016.1149250

To link to this article: http://dx.doi.org/10.1080/2150704X.2016.1149250

Published online: 22 Feb 2016.

REMOTE SENSING LETTERS, 2016
VOL. 7, NO. 5, 466–475
http://dx.doi.org/10.1080/2150704X.2016.1149250

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Temporal partial unmixing of exotic salt cedar using Landsat time series

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ABSTRACT

In the south-western United States, the rapid colonization of exotic salt cedar (*Tamarix* spp.) along the riparian corridors poses a serious threat to the native plant diversity. Monitoring the salt cedar abundance in diversified riparian ecosystems is critically essential for evaluating the biodiversity loss and developing corresponding restoration strategies. To date, it still remains a significant challenge to estimate the abundance of plant species within a pixel, as many plants share similar spectral signatures. This challenge is even more daunting in species diverse ecosystems due to the difficulty of securing all the endmembers (e.g. plant species) in unmixing procedures. The objective of this study is to introduce a new concept, temporal partial unmixing, to estimate the relative abundance of plant species using Landsat time series. Temporal partial unmixing only requires the signature of the target endmember, but it emphasizes the importance of the temporal dimension of the target signature in estimating the corresponding abundance. Two types of temporal signatures that capture the phenological trajectory of the salt cedar growth were devised in this study. Compared to the traditional partial unmixing method (R^2 = 0.35), temporal partial unmixing that exploited the temporal signatures greatly improved the relative abundance estimation accuracy (R^2 = 0.56 or 0.49). It is concluded that the proposed temporal partial unmixing, along with the readily available Landsat imagery, offers unprecedented opportunities to monitor the abundance dynamics of plant species, especially in spatially heterogeneous landscapes.

ARTICLE HISTORY
Received 12 November 2015
Accepted 25 January 2016

1. Introduction

The rapid spread of non-native species has compromised ecosystem functions and posed significant threats to the ecological biodiversity at the global scale. Over the past century, the landscapes along the riparian corridors in the south-western United States have been altered profoundly due to the widespread colonization of exotic salt cedar (*Tamarix* spp.), a woody shrub plant. Monitoring the salt cedar abundance in diversified riparian ecosystems is thus notably crucial for conservation practitioners to evaluate the biodiversity loss and develop corresponding restoration strategies

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(Nagler et al. 2011). As the benchmark in remote sensing, spectral mixture analysis has been widely used to estimate the fractional coverage of typical land covers (i.e. endmembers) within a pixel (Adams, Smith, and Johnson 1986). However, spectral unmixing of vegetation at the species level presents a continuing challenge, as various co-occurring plant species may exhibit similar spectral signatures in a remotely sensed image. The limited spectral information possessed by a single image is not sufficient to obtain subpixel abundance estimations of vegetation species (e.g. salt cedar).

Temporal mixture analysis (TMA) opens up new opportunities in the unmixing procedure, through characterizing the temporal signatures of land cover types (Lobell and Asner 2004; Somers and Asner 2013a). Instead of scrutinizing the spectral signatures of typical land covers at a single time point, TMA takes into account their seasonal phenological trends in estimating the subpixel fractions, given that their fractions do not vary through time. To date, TMA has been mostly conducted using the time series of high temporal resolution Moderate Resolution Imaging Spectroradiometer (MODIS) imagery (Lobell and Asner 2004; Yang et al. 2012; Knight and Voth 2011; Shao and Lunetta 2011). Despite the promising unmixing results demonstrated by these studies, the coarse spatial resolution of MODIS imagery (e.g. 250 or 500 m) limited the mapping to relatively homogeneous croplands or general land cover classes (e.g. vegetation and impervious surface). To facilitate the species-level abundance estimation, recently, TMA has been explored with the multi-temporal hyperspectral Earth Observing-1 Hyperion imagery to map the abundance of tree species (Somers and Asner 2013a, 2013b, 2014). Somers and Asner (2014) constructed the endmember (i.e. four tree species) signatures from multiple dates of imagery spanning the growing season to capture the species-specific phenology. The temporal analysis provided a more accurate tree species map compared to conventional unmixing methods. However, the limited spatio-temporal coverage of Hyperion imagery discouraged the evaluation of the role of TMA in estimating the abundance of other targeted plant species or monitoring the species abundance dynamics. Moreover, TMA conducted in these studies (e.g. MODIS-based and Hyperion-based) requires the temporal signatures of all the endmembers, but not all the endmembers can be easily acquired, especially in species diverse riparian ecosystems where salt cedar inhabit. The difficulty in securing all the endmembers presents a great challenge for abundance estimations in TMA.

The objective of this study is to introduce a new concept, temporal partial unmixing, to estimate the relative abundance of plant species using Landsat time series. Temporal partial unmixing only requires the signature of the target endmember, but it emphasizes the importance of the temporal dimension of the target signature in estimating the corresponding abundance. The exotic salt cedar that invaded the diversified riparian ecosystems was served as an example. Three unmixing schemes (see Section 3.1) were designed and compared to investigate the potential of temporal partial unmixing in estimating the relative abundance of salt cedar. The space-borne Landsat imagery represents the current optimal trade-off among the spatial, temporal and spectral resolution in conducting the repeated species-level mapping over wide geographical areas. To be more easily generalized to other plant species, the study was conducted with the readily available Landsat imagery, which has rarely been studied in TMA.

2. Study site and data preparation

2.1. *Study site*

The study site is located along the Rio Grande River near the town of Candelaria, Texas (Figure 1). The climate in the study site is characterized as semi-arid to arid, with average temperatures around 32 °C and amounts of average annual precipitation less than 30 cm. The vegetation communities along the river have been altered significantly in the last century, mainly due to anthropogenic river regulations and dam constructions. As a consequence, the native biotic vegetation has been largely replaced by the exotic salt cedar. Yet the vegetation distributed in the study site is still diverse, including salt cedar (*Tamarix* spp.), willow (*Salix* spp.), mesquite (*Prosopis* spp.), marshy weed (*Limnophila* spp.), poverty weed (*Iva axillaris* Pursh) and many types of non-woody species.

2.2. *Data preparation*

The study area is covered by two overlapping Landsat footprints (path 31, row 39, and path 32, row 39). The Landsat time series in 2005 was used to evaluate the proposed method in salt cedar abundance estimation. Three unmixing schemes were designed with the Landsat time series (see Section 3.1). All the Landsat imagery were radiometrically corrected to the surface reflectance with the Landsat Ecosystem Disturbance

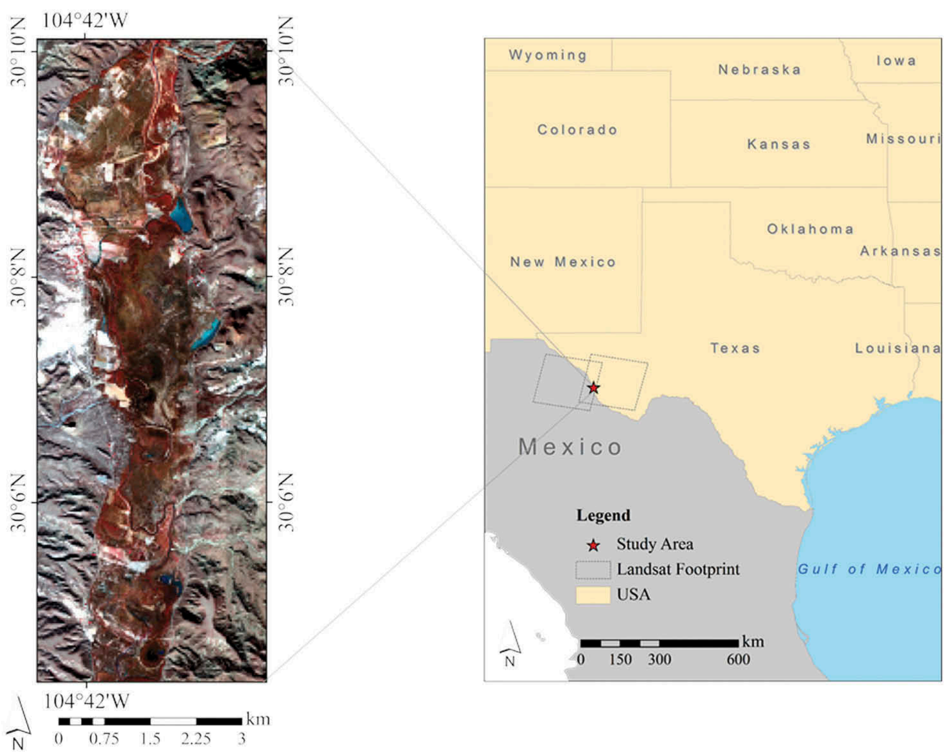

Figure 1. Geographic location and false colour composite image of the study site.

Adaptive Processing System (LEDAPS) (Masek et al. 2006). The corrected images were then co-registered to the reference data with the root mean square errors less than 0.2.

The reference data in this study was obtained from the Airborne Imaging Spectroradiometer for Applications (AISA) image. The AISA image has 61 bands ranging from 400 to 1000 nm with a spatial resolution of 1 m. The AISA was acquired on 21 December 2005, which coincided with the leaf senescence stage of salt cedar. The colour of salt cedar leaves at this phenological stage turns orangish-yellow and can be more easily distinguished from the darker tones of native species (Wang et al. 2013). Two field trips were conducted in 2004 and 2005 to collect the ground reference data for classifying the AISA image. Support vector machine (SVM) was used to classify the AISA image into the class salt cedar and others (Wang and Zhang 2014). The user's accuracy of salt cedar calculated from the ground reference data was 95% and the producer's accuracy was 93%. The classified AISA image was spatially resampled to the Landsat scale (30 m) with the fraction of salt cedar calculated for each pixel. To evaluate the performance of temporal partial unmixing, the salt cedar fractions were then sampled using abundance ranges (i.e. 0–10%, 10–20%, etc.). Fifty pixels in each abundance range were randomly selected as the testing samples. In total there were 500 testing samples.

3. Methods

A flow chart of the main methods utilized in this study was presented in Figure 2. Three unmixing schemes were devised with the Landsat time series to estimate the relative

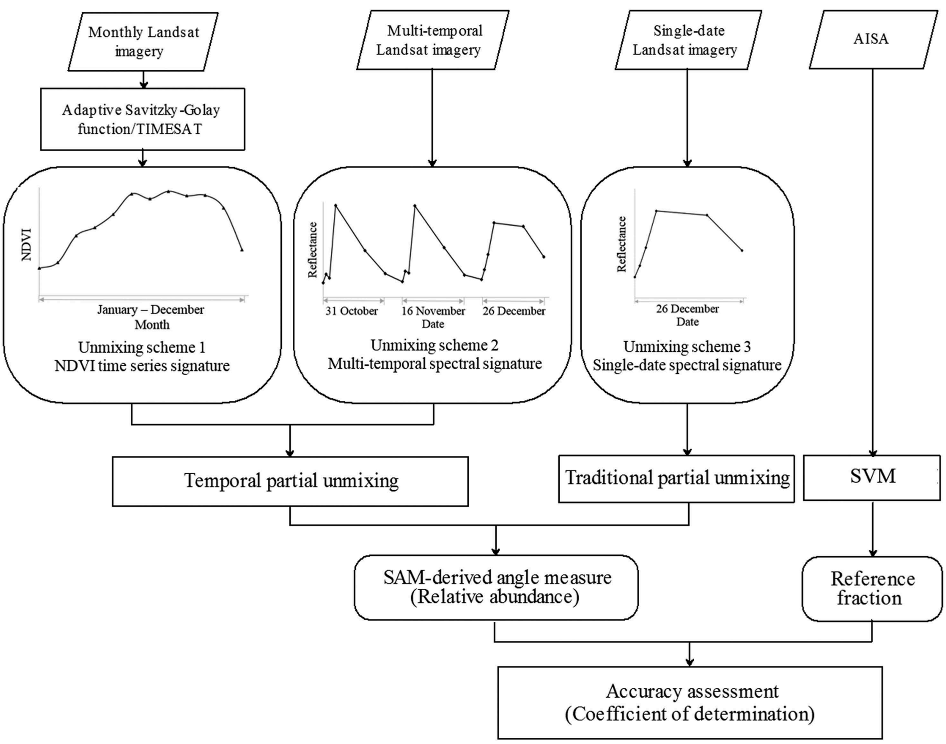

Figure 2. Flow chart of the methodology.

abundance of salt cedar (Section 3.1). The adaptive Savitzky–Golay function was employed to preprocess (or smooth) the Landsat time series of normalized difference vegetation index (NDVI) (Section 3.2). Temporal partial unmixing proposed in this study was introduced in Section 3.3.

3.1. *Three unmixing schemes*

The unmixing schemes depicted how the signatures of endmembers were defined in the unmixing process. To evaluate the role of temporal partial unmixing in salt cedar abundance estimation, three unmixing schemes were devised: (1) the NDVI time series signature from the monthly Landsat imagery, (2) the multi-temporal spectral signature from the multiple-date Landsat imagery and (3) the spectral signature from the single Landsat image acquired on 26 December 2015 (Table 1). Based on the field reconnaissance, the salt cedar fraction within each pixel was assumed to be constant during the temporal mapping period. The first two schemes were specifically designed for temporal unmixing, and the third scheme designed for the traditional spectral unmixing was served as a baseline for comparison.

All Landsat Thematic Mapper (TM) images covering the study site in 2005 were scrutinized. One Landsat TM image was selected in each month to approximate the equally spaced monthly time series. Due to the cloud contamination, no Landsat TM images were available in February or December. The image in February was interpolated by the adjacent images in January and March. However, the month December has been demonstrated in previous studies as the optimal time window to spectrally discriminate salt cedar from native vegetation, as salt cedar foliage turns a distinct orangish-yellow colour during this period (Silván-Cárdenas and Wang 2010). Thus the Landsat Enhanced Thematic Mapper Plus (ETM+) Scan Line Corrector (SLC)-off images acquired in December were explored. The Landsat ETM+ image acquired on 26 December 2015 was found to be of high quality and utilized to construct the monthly Landsat time series. NDVI was calculated for each image of the monthly time series. The smoothed NDVI time series (see Section 3.2) was then served as the first unmixing scheme, as time series of NDVI carries valuable information about the phenological development of vegetation species (Diao and Wang 2014).

Instead of the temporal NDVI signature, the second scheme investigates the multi-temporal spectral signature of vegetation species at several phenological stages. The Landsat imagery acquired on 31 October, 16 November and 26 December 2005 were used to create the multi-temporal spectral signatures of land covers. During this multi-temporal period, the salt cedar foliage changed from green to orange, to yellow, and then to brown before defoliation. The multi-temporal spectral signature of salt cedar was used to trace its phenological process from leaf-on to leaf-off (i.e. the process of leaf

Table 1. Three unmixing schemes designed in this study.

Unmixing scheme	Type	Description
NDVI time series signature	Temporal partial unmixing	One Landsat image was acquired in each month of the year 2005. NDVI was calculated for each Landsat image to create the time series.
Multi-temporal spectral signature	Temporal partial unmixing	Three Landsat images were acquired on 31 October, 16 November and 26 December 2005, respectively. Six bands in each image were used. In total there were 18 bands.
Single-date spectral signature	Traditional partial unmixing	A Landsat image was acquired on 26 December 2005. Six bands were used to construct the spectral signature.

senescence), and to capture the gradual change of its leaf colour (i.e. spectral reflectance). We assumed that the phenological difference between plant species at the leaf senescence stage can be better captured with process-based multi-temporal spectral signatures, rather than single date-based spectral signatures. These three months have also been found to be the most crucial in discriminating salt cedar from native vegetation (e.g. mesquite and willow) throughout the year (Diao and Wang 2015). For each selected Landsat image, the spectral information of the six bands (except the thermal band) was used. In total there were 18 bands in the multi-temporal unmixing scheme. As a baseline for comparison, the spectral signature from the single Landsat image acquired within the optimal detection window (i.e. 26 December 2015) was served as the third unmixing scheme. Six bands (except the thermal band) on this single date were used in the unmixing process. The design of the third scheme was for the traditional spectral mixture analysis, since only the spectral information on a single date was involved.

3.2. *Time series smoothing*

The adaptive Savitzky–Golay function in TIMESAT was employed to smooth the monthly NDVI time series and to reduce the influence of extreme NDVI values (Jönsson and Eklundh 2004). The smoothing function is capable of maintaining distinct vegetation time series while smoothing out the noise caused by poor atmospheric and background conditions. It performs a polynomial least square fit to the data within a local window and allows the data smoothing without forcing a given mathematical function. To further account for the negatively biased noise (e.g. undetected atmospheric conditions), the smoothing function was adapted to the upper envelope of the NDVI profile with the TIMESAT software. The smoothed Landsat NDVI time series was then served as the first unmixing scheme in the subsequent analysis.

3.3. *Temporal partial unmixing*

In the linear mixture analysis, the signature of a pixel is modeled as a linear combination of endmember signatures, weighted by their fractional coverage in the pixel. If the signature denotes the spectral reflectance profile from a single-date remotely sensed image (e.g. unmixing scheme 3), the analysis is then called spectral mixture analysis (Adams, Smith, and Johnson 1986). Moreover, the signature can be expanded to the temporal dimension to accommodate the phenological variability, provided that endmember fractions do not vary through time (Lobell and Asner 2004). The temporal signature can be constructed either in terms of vegetation index (e.g. unmixing scheme 1) or spectral reflectance (e.g. unmixing scheme 2) from the time series of satellite imagery. The corresponding analysis is named temporal mixture analysis. TMA has been demonstrated to have good potentials to improve the discrimination between plant species that maintain distinct phenological cycles (Somers and Asner 2013a).

A complete unmixing of an image is not always possible, especially in species diverse ecosystems. In previous studies, partial unmixing methods, such as spectral angel mapper (SAM), matched filtering (MF), mixture tuned matched filtering (MTMF), and constrained energy minimization (CEM), have been developed for estimating the relative abundance of the target class (Boardman, Kruse, and Green 1995; Pour and Hashim

2012). However, partial unmixing studies are still very lacking, mainly due to the limited spectral signature information of the target and the uncertainty of the spectral reflectance of backgrounds in a single image. Temporal partial unmixing is newly proposed in this study to define the TMA where only the signature of the target (e.g. salt cedar) is required. It also assumes that endmember fractions do not vary through time. Temporal partial unmixing is built on the partial unmixing methods, but exploits the temporal signature (instead of the traditional spectral signature) of the target in estimating its corresponding abundance within a pixel. Temporal partial unmixing is particularly desirable in estimating the relative abundance of the targeted plant species, as it is capable of incorporating the phenological trajectory of plant growth into the partial unmixing process. In this study, two temporal signatures (unmixing schemes 1 and 2) were investigated in temporal partial unmixing. The unmixing results were evaluated through comparison to that of spectral-signature-only-based (unmixing scheme 3) partial unmixing. Eighteen pixels that contained pure salt cedar (100%) were identified from the resampled AISA classification result. The target signature for each scheme was obtained by averaging the corresponding signatures of the 18 pixels (Figure 2).

As a partial unmixing method, SAM was used as an example in temporal partial unmixing to investigate the role of the temporal phenological information in partially unmixing of vegetation species. SAM determines the similarity between image signatures and reference (or target) signatures by calculating the angle between them (Kruse et al. 1993). For example, in unmixing scheme 1, the reference signature is the monthly NDVI time series of pure salt cedar. SAM calculates the similarity between the monthly NDVI time series of each pixel to that of the reference. A smaller angle represents a higher likelihood of signature matching to the pure salt cedar population. As the angle widens, the pixel signature deviates more from the pure salt cedar signature, and contains a greater mix of the target and backgrounds. Thus the SAM-derived angle measure can be used to determine the relative abundance of salt cedar. To assess the accuracy of partial unmixing results, the coefficient of determination (R^2) was calculated for each scheme. The coefficient of determination is a measure to evaluate the proportion of variance in the reference salt cedar abundance data that can be explained by the relative abundance measure using SAM.

4. Results and discussion

Three unmixing schemes were designed and evaluated with the partial unmixing method (e.g. SAM). Two types of temporal signatures and the traditional spectral signature were investigated in this process. The value of R^2 was used to evaluate the performance of partial unmixing for each scheme with the testing samples (Figure 3). For all three proposed schemes, the salt cedar reference fraction presented a negative relationship with the SAM-derived angle measure from partial unmixing, which reinforced that a narrower angle in the signature matching was associated with a higher fractional coverage of the target salt cedar within a pixel. The highest value of R^2 was achieved with the unmixing scheme 2 (R^2 = 0.56), followed by the unmixing scheme 1 (R^2 = 0.49), and the lowest value was from the unmixing scheme 3 (R^2 = 0.35). Through comparing the three evaluation plots, we found that with the single-date-spectral target signature (unmixing scheme 3), the reference data of salt cedar abundance were scattered the most along the regression line. The variation in

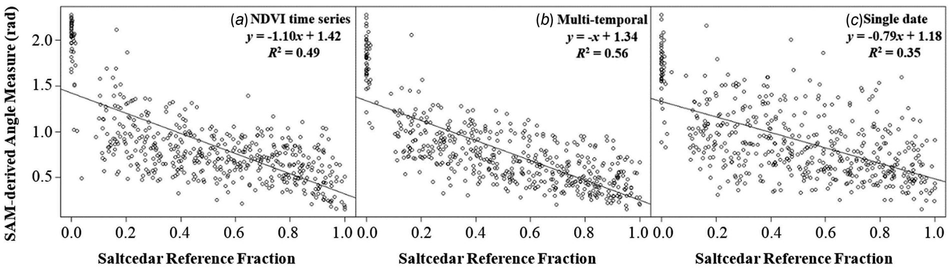

Figure 3. Coefficient of determination (R^2) for relative abundance estimates of salt cedar using three unmixing schemes.

reference abundance data was explained the least by this traditional partial unmixing result. In contrast, the testing samples presented a much clearer trend in Figure 3a and 3b. About 20% more variation in the reference data can be explained by the result of the temporal partial unmixing in which the multi-temporal spectral signature of the target was exploited.

Species-level abundance estimation remains a continuing challenge, especially in diversified landscapes. It is difficult or even impossible to survey all the endmembers in species diverse riparian ecosystems where salt cedar invaded. Partial unmixing methods that only require the target information are more suitable for handling this diverse system. Yet it is still not clear what types of the target information can fully accomplish the potential of partial unmixing. The spectral information offered by a single remotely sensed image is traditionally utilized for this purpose. As for exotic salt cedar, the spectral signature designed in unmixing scheme 3 can be deemed as optimal, as salt cedar foliage colour is the most distinguishable from native species during the leaf senescence stage. However, compared to this single-date-optimal-spectral signature, the temporal signatures devised in this study still greatly improved the relative abundance estimation accuracy. This remarkable increase is essentially owing to the plant phenological trajectory characterized in temporal partial unmixing. The seasonal variation captured by temporal partial unmixing facilitates the distinction of plant species with different phenological trajectories. When only the target signature can be acquired, the temporal signature that encompasses extended observation periods is particularly valuable in characterizing the plant species. The readily available Landsat data, combined with the recently launched Sentinel-2, Proba-V and Gaofen-1, provide unique opportunities to create such temporal signatures. Hence, temporal partial unmixing, with temporal signatures portrayed, shows considerable potential for mapping the relative abundance of salt cedar in species diverse riparian ecosystems.

Two types of temporal signatures were investigated in temporal partial unmixing, namely the NDVI time series signature and the multi-temporal spectral signature. As a commonly used vegetation index, NDVI is mainly developed to measure the photosynthetic activities of vegetation, and is calculated based on the red and near-infrared bands. Since the advent of high temporal resolution satellites (e.g. MODIS), NDVI time series has been extensively studied to characterize the phenological patterns of homogeneous (or general) land covers. The multi-temporal spectral signature, on the other hand, is acquired from different imaging dates to characterize the key phenological stages of vegetation. In this study, the multi-temporal spectral signature that encompassed the month October, November and December was constructed to approximate the leaf senescence stage of salt cedar. Instead of pinpointing a single date, the multi-temporal spectral signature simulated the phenological process of salt cedar from leaf-on to leaf-off (i.e. the process of leaf senescence). Compared to the NDVI time series signature, temporal partial unmixing with the multi-temporal spectral signature achieved a higher estimation accuracy. This improved accuracy is partly due to the richer spectral information carried by the multi-temporal spectral signature, which contains six bands (i.e. visible to shortwave infrared regions) rather than the vegetation index derived from the two bands (i.e. the red and near-infrared bands) of the imagery. Moreover, the multi-temporal spectral signature targets only the key phenological stages, the importance of which may be diluted by the entire growing season scrutinized by the NDVI time series. The role of temporal signatures in temporal partial unmixing still needs to be further evaluated before the proposed method is generalized to other plant species. Besides, in this study, only the average of target signatures was used as the endmember signature. Endmember variability, caused by differential illumination conditions and scene components, was thus not accounted for. The influence of endmember variability on the estimation result needs to be tested in future studies.

5. Conclusions

In the south-western United States, the landscapes along the riparian corridors have been transformed profoundly over the last century, due to the rapid expansion of exotic salt cedar. Mapping the salt cedar abundance at the regional scale is urgently important to guide the systemic restoration of riparian ecosystems. However, the riparian ecosystems where salt cedar colonizes are particularly species diversified. The acquisition of all the endmembers remains a significant challenge. To ease this challenge, temporal partial unmixing was introduced in this study to conduct the partial unmixing with only the temporal signature of the desired species required. Compared to the traditional single-date-optimal-spectral signature, the temporal signatures devised in this study greatly improved the relative abundance estimation accuracy. As the current optimal trade-off among the spatial, temporal and spectral resolution, Landsat imagery creates unprecedented opportunities in conducting the repeated species-level mapping over wide geographical areas. Temporal partial unmixing, with the temporal signatures secured by the Landsat time series, offers considerable promise in mapping the relative abundance of plant species in diversified ecosystems.

Disclosure statement

No potential conflict of interest was reported by the authors.

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