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Comparing land surface phenology with leafing and flowering observations from the PlantWatch citizen network

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ABSTRACT

Annual maps of the remote sensing green-up date derived from SPOT-VEGETATION data were compared to the phenological observations collected by the PlantWatch citizen science project across Canada between 1998 and 2012. Green-up dates were found to relate to the leaf-out dates for four woody species (*Populus tremuloides*, *Acer rubrum*, *Syringa vulgaris*, *Larix laricina*), with a RMSE from 13.6 to 15.6 days. This was true for all landcover types except in pixels where agriculture or water bodies were dominant. This is less accurate than the results from previous studies for boreal Eurasia (RMSE = 8.7 days), with phenology data from an operational network. When data were aggregated at a regional level, the remote sensing green-up date matched well with the interannual variations in leafing and also in flowering of most of the recorded species. These included spring events for trees, shrubs and non-woody plants which were either native to Canada or introduced. For most plants, spring flowering and leafing times are functions of accumulated temperature. For this reason, plant species develop in a predictable sequence, and interannual variations in this cohort of species leafing and flowering are correlated. This explains the correlation with remote sensing green-up. Data from this volunteer PlantWatch network proved consistent with independent satellite data, suggesting that combining the two will strengthen the future capacity to monitor vegetation changes.

1. Introduction

Phenology is both a response to and a driver of global changes (Richardson et al., 2013). Besides reflecting the impact of climate change (Badeck et al., 2004; Parmesan & Yohe, 2002; Root et al., 2003; Walther, 2010; Walther et al., 2002), phenological shifts affect the functioning of ecosystems (Baldocchi, Falge, Olson, et al., 2001; Both, Van Asch, Bijlsma, Van Den Burg, & Visser, 2009; Chuine, 2010; Picard et al., 2005). Phenological changes and gradients have been assessed through a variety of methods, including ground observations carried out by scientists (Ahas, Aasa, Menzel, Fedotova, & Scheifinger, 2002; Menzel, Sparks, Estrella, et al., 2006; Schwartz, 2013) or by citizens interested in nature (Beaubien & Hamann, 2011a and b; Gazal et al., 2008; "http://obs-saisons.fr"), modelling (Chuine, 2000; Hänninen, 1994; Morin et al., 2009; Schwartz, Ahas, & Aasa, 2006), or remote sensing based methods. Remote sensing methods are used to estimate green-up, also called "land surface phenology", *i.e.* the timing of changes at the scale of a satellite pixel (Reed et al., 1994; Sakamoto et al., 2005; Zhang et al., 2003). Satellites can observe the earth surface frequently enough – if cloud conditions allow it – to catch the gradual changes in the reflectance, and satellite images are available starting in the early 1980s (Moulin, Kergoat, Viovy, & Dedieu, 1997).

During the boreal or temperate spring, the remote sensing green-up date is usually defined as the time at which the pixel starts to green-up or has reached a certain percentage of its maximum summer greenness. Greenness is quantified through a spectral vegetation index combining the reflectance retrieved from the observed radiance in the near infrared domain and in one visible band, based on the absorbance spectrum of chlorophyll. This vegetation index increases as the amount of photosynthetic tissue increases within a pixel. Methodologies to derive the green-up date from these index time series are numerous and can give very different results (White, De Beurs, Idan, et al., 2009). Validation of the green-up date therefore requires a comparison with external data, typically ground observations of plant phenology. Ganguly, Friedl, Tan, Zhang, and Verma (2010) showed that the MODIS collection 5 global green-up product compared well with ground observations at two sites. White et al. (2009) however showed that eight out of ten tested methods gave green-up dates that were very different from ground observations. Ideally, linking phenological observations made on individual plants to green-up dates requires that the observed individuals are representative of their surroundings up to the pixel size.

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This is challenging when the area within the pixel contains a mosaic of land cover types, or when species diversity is high, or when there is a pronounced phenological diversity among individuals of the same species in the pixel. Methods to overcome such drawbacks include reducing the pixel size (Fisher, Mustard, & Vadeboncoeur, 2006; White, Pontius, & Schaberg, 2014), cross-comparing results obtained at different spatial resolution (Fisher & Mustard, 2007), or increasing the number of ground observations within the pixel (Liang, Schwartz, & Fei, 2011).

Delbart, Kergoat, Le Toan, L'Hermitte, and Picard (2005) described a method based on SPOT-VEGETATION reflectance data to estimate the green-up date in boreal regions without the confusion due to reflectance changes during snowmelt. The method uses the Normalized Difference Water Index (NDWI), which is the normalized difference of near infrared (NIR) and short-wave infrared reflectance (SWIR). This index is sensitive to the water content in the plant tissues rather than to chlorophyll (Gao, 1996), and increases during foliation. The green-up dates were compared to ground measurements of deciduous tree leaf appearance date for ten taiga sites in Siberia, showing a root mean square error (RMSE) of 8.7 days. This validation was based on the hypothesis that the Siberian taiga was homogeneous enough in terms of phenology within the SPOT-VEGETATION pixel, due to the large forest fractional cover and to the small number of tree species, to make the field observations representative of the whole pixel in which they were made. The method was further tested at a few more sites in other parts of boreal Eurasia (Delbart et al., 2008) and to one site in Alaskan tundra (Delbart & Picard, 2007). In both cases, the confidence in the green-up date was increased by the agreement found with the date obtained not only by local observation but also by a degree-day model based on daily temperature. Delbart et al. (2008) showed that the green-up date averaged at the regional scale reproduces a large part of the interannual variation in leafing date observations carried out at several locations within the region.

Still, remote sensing methods hold an inherent drawback in that they do not reveal the diversity of plant phenology within the pixel. Diversity comes from the phenological differences between species (interspecific variation) and between individuals of the same species (intraspecific variation). Moreover, as vegetation indices are usually based on spectral signatures that are explained by chlorophyll, and because usually leaf tissue mass is much larger than flower tissue mass, we can assume that green-up – either retrieved from a greenness index or from NDWI – is essentially directly linked to foliage phenology. It may also be indirectly linked to flower phenology, as both spring foliage and flowers develop in response to increasing temperature and thus are correlated to each other.

The objective of this study is to evaluate how the green-up relates to both the leaf and flower phenology of the diverse plant species within the pixel. For this, we carry out a comparison of the green-up date with 743 observations of the date of leaf appearance made on four tree species and several thousand observations of the date of first flowering for 39 species. This large set of phenological observations was collected by Canadian citizens in the framework of the PlantWatch project following a precise protocol (Beaubien & Hamann, 2011a and b; www.plantwatch.ca). We further evaluate if green-up can be used to monitor the interannual variations of plant leafing and flowering dates efficiently.

2. Materials and methods

2.1. SPOT-VEGETATION NDWI estimates of green-up dates, 1998–2012

The algorithm described in Delbart et al. (2005) is applied to the SPOT-VEGETATION (VGT) S10 data for the years 1998 to 2012 (freely available at http://www.vito-eodata.be/PDF/portal/Application.html). S10 data gives a reflectance value for four spectral bands once every ten days. The selected value is the "best" measurement that has been made during the 10 day period, following the "maximum value composite" method (Holben, 1986). The exact date of the selected measurement is given individually for each pixel.

The objective of our method is to provide an estimation of the date on which the ecosystem greens up. To avoid false detection due to snowmelt, the green-up date is retrieved from the seasonal evolution of NDWI as this index decreases during snowmelt and increases during foliage development. Green-up date is taken as the last date in the March–July period at which NDWI has increased by less than 20% of its total increase in this period. Here, the algorithm is applied at the full VGT spatial resolution (0.0089°). The algorithm is run for the years 1998 to 2012, to obtain one green-up day map each year.

2.2. PlantWatch observations and land cover map

The phenological observations are carried out and reported in the database by citizen scientists in the framework of the PlantWatch project (*www.plantwatch.ca*). We use *in situ* first-bloom data for 39 species (Table 1), and leaf-out data for four selected woody plants *Acer rubrum*, *Syringa vulgaris*, *Populus tremuloides* and *Larix laricina* (see spatial distribution in Fig. 1). The description of all species and their observation protocols can be found on the PlantWatch website. Data were quality checked: the observations reported from the Churchill Northern Studies Centre project to the PlantWatch database were discarded because of issues with geographic coordinates and some taxonomic errors.

The data are stratified according to the GLC2000 landcover map (Bartholomé & Belward, 2005), which provides 22 classes (simplified in Fig. 1). This dataset was derived from SPOT-VEGETATION time series

Table 1
Scientific and common names of the species observed in the PlantWatch project and used in this study.

Scientific name (* are introduced species)	Common name
Acer rubrum	Red Maple
Achillea millefolium	Yarrow
Amelanchier	Saskatoon or Serviceberry
Anemone patens	Prairie Crocus
Arctostaphylos uva-ursi	Bearberry
Betula papyrifera/B. neoalaskana	Paper Birch
Clintonia borealis	Blue-bead Lily
Clintonia uniflora	Queen's Cup
Cornus canadensis	Bunchberry
Dryas integrifolia, D. octopetala	Mountain Avens
Elaeagnus commutata	Wolf Willow
Epigaea repens	Mayflower
*Forsythia suspensa**	Weeping Forsythia
Fragaria virginiana/F. vesca	Wild Strawberry
Galium boreale	Northern Bedstraw
Houstonia caerulea	Bluets
Larix laricina	Larch
Linnaea borealis	Twinflower
Lupinus arcticus	Arctic Lupine
Maianthemum stellatum	Star-flowered Solomon's Seal
Myrica gale	Sweetgale
Nymphaea odorata	White Water Lily
Pinus contorta	Lodgepole Pine
Populus tremuloides	Aspen Poplar
Prunus virginiana	Choke Cherry
Ranunculus glaberrimus	Sagebrush Buttercup
Rhododendron canadense	Rhodora
Rhododendron groenlandicum	Labrador Tea
Rubus chamaemorus	Cloudberry
Saxifraga oppositifolia	Purple Saxifrage
Saxifraga tricuspidata	Prickly Saxifrage
*Syringa vulgaris**	Common Purple Lilac
*Taraxacum officinale**	Dandelion
Thermopsis rhombifolia	Golden Bean
Trientalis borealis	Starflower
Trillium grandiflorum	Trillium
*Tussilago farfara**	Coltsfoot
Vaccinium vitis-idaea	Cranberry
Viola adunca	Early Blue Violet

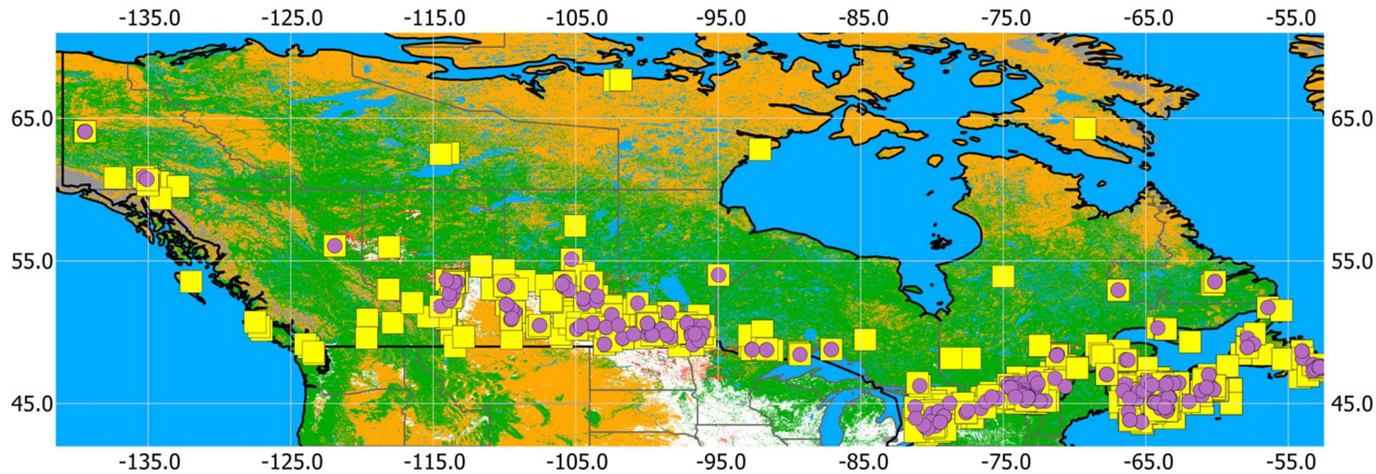

Fig. 1. Spatial distribution of *in situ* observations superimposed over a land cover map. Purple disks: *Populus tremuloides*, *Acer rubrum*, *Syringa vulgaris* and *Larix laricina* leaf-out. Yellow squares: all species first flowering. Background (simplified from GLC2000); grey: bare, urban, ice areas. Red: mosaic of agricultural lands and other types of lands. Green: forests. Orange: grass and shrublands. White: purely agricultural lands.

in 2000. Because the classes only represent the dominant landcover in the pixel, many PlantWatch observations were made at locations within a pixel classified as water or agriculture.

2.3. Comparing green-up to phenological events at the pixel level

First, we study the relationship between *in situ* leaf-out date and the green-up date, for each species and each landcover type, including water and pure agriculture pixels, using 743 leaf-out observations.

Second, we quantify the relationship between green-up and leaf-out, and between green-up and first bloom. Observation sites belonging to pixels classified as pure agriculture or water are excluded. Statistics include the number of observations, the mean lag between green-up and the phenological event, the RMSE and its unsystematic ($RMSE_u$) and its systematic ($RMSE_s$) components (Willmott, 1982) that gives respectively the dispersion around the best linear fit and the distance between this linear fit and the 1:1 line, the correlation *r* and its associated p-value.

For the events that are found significantly correlated at $p < 0.05$, we also test if the green-up time series allows following the interannual variations in the leafing and flowering events at the pixel level. For each series, correlation and associated p-value are calculated.

2.4. Aggregating data at a regional level

We compare the interannual variations of green-up date with those of flowering and leafing at a regional level. The choice of the boundaries of the regions is based on the observation availability and clustering. The seven regions are: Newfoundland (52.5–59.48°W; 46.64–51.70°N), New Brunswick and Nova Scotia (59.6–67.05°W; 43.32–47.40°N), the Montreal-Quebec area (71.2–74.83°W; 45–47.30°N), the Toronto area (75.3–81.38°W; 42.5–46°N), South Manitoba (95.5–101.2°W; 48.9–52.54°N), South Saskatchewan (101–110°W; 48.9E–55°N), South Alberta (110–116°W; 48.9–55°N) .

In order to build a regional time series for each species event, considering that each location time series may hold a systematic bias relative to the zonal average and may be incomplete, we adapted the method 3 of Hakkinen, Linkosalo, and Hari (1995). This method is applied for each species separately within a region. First observation time series with only one year observation are discarded.

For year i, the aggregated date is:

$$y_i = \frac{\sum_j \left(x_{ij} + b_j\right)}{n_i}$$

where x_{ij} is the date of observation at location j for year i, n_i is the number of observations for year i in the region, and b_j is the bias specific to the location j. We first aggregate the two time series that have the largest number of common years by 1/ shifting the second series towards the first one by b_j (the bias of the second series relatively to the first one), and 2/ averaging them. We then repeat the operations for each remaining series individually taking the already aggregated series as the reference series towards which one series at location j is shifted by b_j (the bias relatively to the reference series) and to which it is averaged (while averaging, the weight of the reference series being the number of series that were already aggregated; this weight incremented during the process). The procedure is stopped if the remaining series do not have common years with the reference series. Finally, we shifted the aggregated series by subtracting the average of all b_j. We discard the aggregated series if it is made of less than 9 year observations, and thus we do not have series for the Toronto and Alberta regions.

The regional green-up date is calculated as the average green-up date from pixels corresponding to all observation sites. Thus the set of pixels remains the same for all years, but excludes pixels given as pure agriculture or as water-dominated by GLC2000.

3. Results

3.1. Comparing green-up to observations at the pixel level

Green-up date appears significantly related to *P. tremuloides*, *L. laricina*, *A. rubrum* and *S. vulgaris* leaf-out observations for all landcover types, except for water dominated and agricultural pixels (Fig. 2), where the seasonal water and cropland reflectance changes partly hide the changes in reflectance due to tree foliation.

For other landcover types, green-up is found to be a few days earlier than tree leaf-out, RMSE ranges from 13.6 to 15.6 days, corresponding both to a systematic advance and to some dispersion, but green-up is strongly correlated with leaf-out observations for the four species ($p < 0.0001$) (Table 2). Moreover, green-up is correlated to most of the species' first flowering dates (Table 3), even with large time lags, and this correlation is accompanied by the fact that the range of $RMSE_u$ values is similar to that for leafing events (Table 2). This means that even if green-up comes earlier or later than species' flowering dates, it follows the variation in the observed dates, which is consistent with the idea that both are responding to accumulated temperature. Moreover, green-up follows the interannual variations in observed phenology in some cases (*e.g.* Fig. 3), but not for all series. The correlation between green-up and *in situ* observations is positive and significant

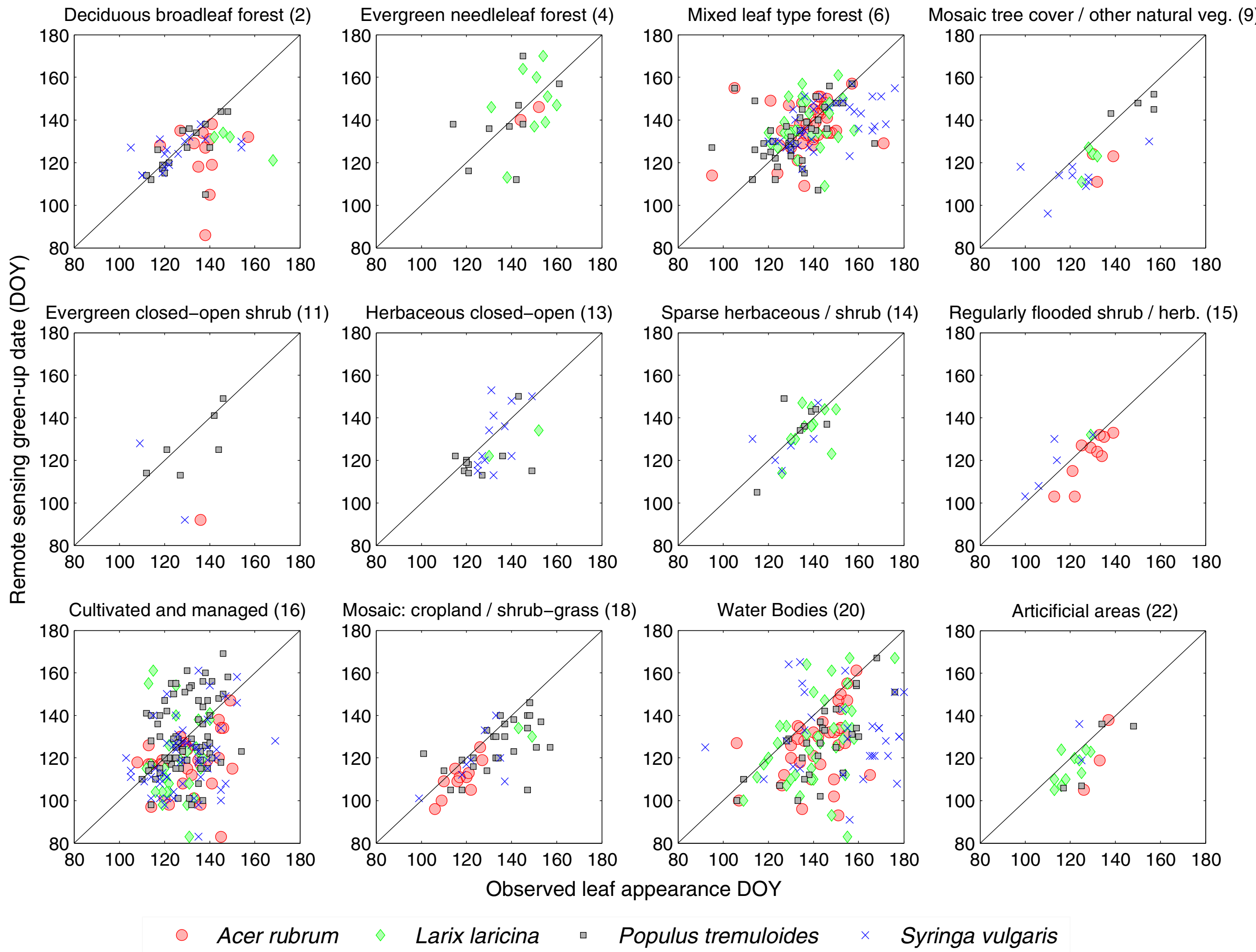

Fig. 2. Comparison of remote sensing green-up dates with *in situ* observations for all landcover types indicated by the class type (class number), for the four tested tree species.

($p < 0.05$) for 44% (8 out of 18) of the longer than 10 year series, but this ratio falls to 25% (12 out of 48), 20% (26 out 131) and 12% (47 out of 377) when considering shorter series (respectively longer than 7, 5 and 2 years). The small number of long series does not allow distinguishing scores between species and events.

3.2. Comparing green-up to observations at the regional level

At the regional level green-up time series correlates strongly with several species phenology in each of the five regions (Fig. 4, Table 4). Green-up correlates with tree species flowering and leafing, shrub flowering, and herbaceous non-woody plant flowering. It does not correlate in any region for only two species (*Forsythia suspensa* and *Houstonia caerulea*) flowering. Among the introduced species, the flowering of two of them (*Tussilago farfara* and *F. suspensa*) shows low correlation with green-up whereas the other two (*S. vulgaris* and *Taraxacum officinale*) display high correlation.

For Newfoundland (Fig. 4a), green-up correlates significantly with several species' flowering mainly because it matches the large observed flowering time variations between 1999 and 2001 and the late spring in 2011, but did not match the other small interannual variations.

For the other four regions (Fig. 4b to e), green-up matches quite well with the variations in both flowering and leafing of several species, even for events that occur quite a bit earlier or later than green-up, like *S. vulgaris* flowering in the New Brunswick–Nova Scotia region. However, the correlation with one species event changes from one region to the other, maybe in relation to the species abundance in each region: for example green-up and *P. tremuloides* leafing are strongly correlated in Manitoba, where *P. tremuloides* is a more dominant forest tree, but uncorrelated in New Brunswick–Nova Scotia where this species is a small component of a more diverse forest. In contrast, interannual variations in the flowering date of other plant flowering, as different as *Amelanchier*, *Cornus canadensis*, *Fragaria virginiana/vesca* or *T. officinale*, correlate with green-up in all or almost all regions.

Table 2
Statistics of the comparison between the remote sensing green-up dates and the *in situ* ground observations of leafing out, based on all observations across Canada excluding observations carried out at a location considered as water or agricultural land in GLC2000. N is the number of observations. The average lag is the mean of the difference between remote sensing green-up date minus the observed date (negative time lag indicates that green-up occurs earlier than leaf-out). RMSE, $RMSE_u$, $RMSE_s$: root mean square error, and its unsystematic and systematic components. *r*: Pearson correlation.** mark indicates green-up and leaf-out are significantly correlated with $p < 0.0001$.

	N	Average lag (days)	RMSE (days)	$RMSE_u$ (days)	$RMSE_s$ (days)	r
Populus tremuloides	133	−3.18	13.61	11.46	7.35	0.51**
Larix laricina	80	−3.89	13.54	11.73	6.77	0.50**
Acer rubrum	86	−5.64	15.02	13.00	7.53	0.49**
Syringa vulgaris	104	−5.67	15.65	10.60	11.51	0.70**

4. Discussion and conclusion

Citizen science is a promising option to obtain country-wide or world-wide datasets of phenological observations at the species level,

Table 3
Statistics of the comparison between the remote sensing green-up dates and the ground observations of flower first-bloom. Same details as in Table 2 caption, and * mark indicates significant correlation with $p < 0.05$ (** indicates $p < 0.0001$).

	N	Average lag (days)	RMSE (days)	$RMSE_u$ (days)	$RMSE_s$ (days)	r	
Acer rubrum	157	10.8	17.9	12.5	12.8	0.45	**
Achillea millefolium	80	−3.9	13.5	11.7	6.8	0.50	**
Amelanchier	226	−10.5	18.7	14.0	12.4	0.49	**
Anemone patens	127	14.9	21.4	12.3	17.5	0.36	**
Arctostaphylos uva-ursi	59	−4.1	13.7	12.8	4.9	0.65	**
Clintonia borealis	172	−18.4	22.8	12.3	19.2	0.63	**
Cornus canadensis	238	−22.5	26.9	13.4	23.4	0.35	**
Dryas integrifolia/D. octopetala	19	−11.1	15.9	10.8	11.6	0.90	**
Elaeagnus commutata	22	−32.0	33.5	9.8	32.0	0.57	*
Epigaea repens	78	13.9	21.8	12.7	17.7	0.02	
Forsythia suspensa	48	4.9	13.4	12.2	5.6	0.48	*
Fragaria virginiana/F. vesca	297	−6.8	16.7	13.8	9.4	0.41	**
Galium boreale	22	−46.3	47.6	10.0	46.6	0.46	*
Houstonia caerulea	21	−1.3	18.7	16.9	7.9	−0.09	
Larix laricina	89	5.9	16.4	13.5	9.4	0.31	*
Linnaea borealis	21	−31.9	35.6	13.7	32.9	0.31	
Lupinus arcticus	20	−11.5	27.3	6.1	26.7	−0.48	*
Maianthemum stellatum	24	−20.2	22.3	9.5	20.2	0.63	*
Myrica gale	24	7.3	20.2	15.5	12.9	0.14	
Populus tremuloides	175	15.0	21.6	11.9	18.0	0.44	**
Prunus virginiana	72	−19.1	23.0	12.1	19.5	0.50	**
Rhododendron canadense	108	−13.7	20.3	13.1	15.5	0.37	**
Rhododendron groenlandicum	114	−20.6	23.3	10.8	20.7	0.72	**
Saxifraga tricuspidata	18	−10.3	13.5	8.5	10.5	0.77	*
Syringa vulgaris	314	−20.5	24.3	12.2	21.0	0.65	**
Taraxacum officinale	367	−0.7	15.3	14.2	5.7	0.49	**
Trientalis borealis	178	−20.6	24.8	13.2	20.9	0.54	**
Trillium grandiflorum	79	−6.5	13.1	11.0	7.1	0.40	*
Tussilago farfara	148	28.1	34.4	15.4	30.7	0.09	
Vaccinium vitis-idaea	27	−19.8	23.9	12.7	20.3	0.31	

with high spatial density at least in some places. Such initiatives have contributed to an understanding of local climate influences on phenology *e.g.* the urban heat island effect (Gazal et al., 2008). Citizen-based science is revealed here to be very useful to further understand the satellite remote sensing signal. Parts of the PlantWatch database have already been used to calibrate (Kross, Fernades, Seaquist, & Beaubien, 2011) or evaluate (Pouliot, Latifovic, Fernandes, & Olthof, 2011; White et al., 2009) remote sensing green-up products. Here we use all available observations over the fifteen years 1998–2012 to evaluate the ability of a remote sensing green-up dataset to reproduce the spatial and interannual variations in phenology.

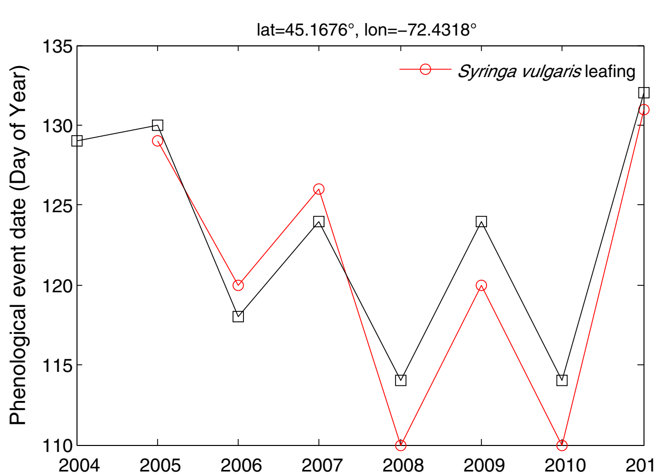

Fig. 3. A selected sample of time series of phenological events and of remote sensing green-up dates, at the pixel level. Black squares represent remote sensing green-up date, red circles represent *Syringa vulgaris in situ* leafing date.

Delbart et al. (2005) showed that the RMSE between the green-up dates and the *in situ* observed leafing out dates was 8.7 days for common trees like birch and larch in Siberia. The RMSE we find here is much larger. In Delbart et al. (2005), the green-up retrieval method was applied over a spatially averaged reflectance dataset, at a spatial resolution of 0.1° instead of 0.0089°. Here we did not favour this option because of the fragmented nature of the landscape. By definition citizen observations are carried out close to where people live, in parks, gardens, or forests or grasslands that may often be next to agricultural or urban lands. Thus we have preferred not to average the reflectance estimated in neighbouring pixels with different land covers, although landcover types are heterogeneous within the 1 km SPOT-VGT pixels and the phenological diversity within each pixel may explain a part of the RMSE. A 13.6 day RMSE is certainly one reason why the interannual variations in green-up are not often correlated with the observations at the pixel level. It appears that when the green-up date is averaged regionally it better correlates with observations, which supports the hypothesis that the lack of spatial averaging of remote sensing data partly explains the lower agreement relatively with Delbart et al. (2005). However, it is not the only reason why green-up and *in situ* phenology are not always correlated, and the length of the *in situ* time series clearly impacts the correlation scores.

Nevertheless, the agreement between green-up date and *P. tremuloides* leafing out date (13.6 day RMSE, 9.3 day mean absolute error, not shown in Table 2) is remarkably better than the 18.5 day mean absolute error found between the leaf expansion date and the start of season (SOS) retrieved from high resolution Landsat data (White et al., 2014), and similar to the best of the methods based on AVHRR data compared in Kross et al. (2011). This is also worse than the ~3 day mean absolute difference between the SOS retrieved from MODIS reflectance time series and the full budburst dates measured on several sites within a 3 by 3 km area (Liang et al., 2011) or the 5 day mean absolute difference between green-up derived from AVHRR and a small sample of PlantWatch leaf-out data (Pouliot et al.,

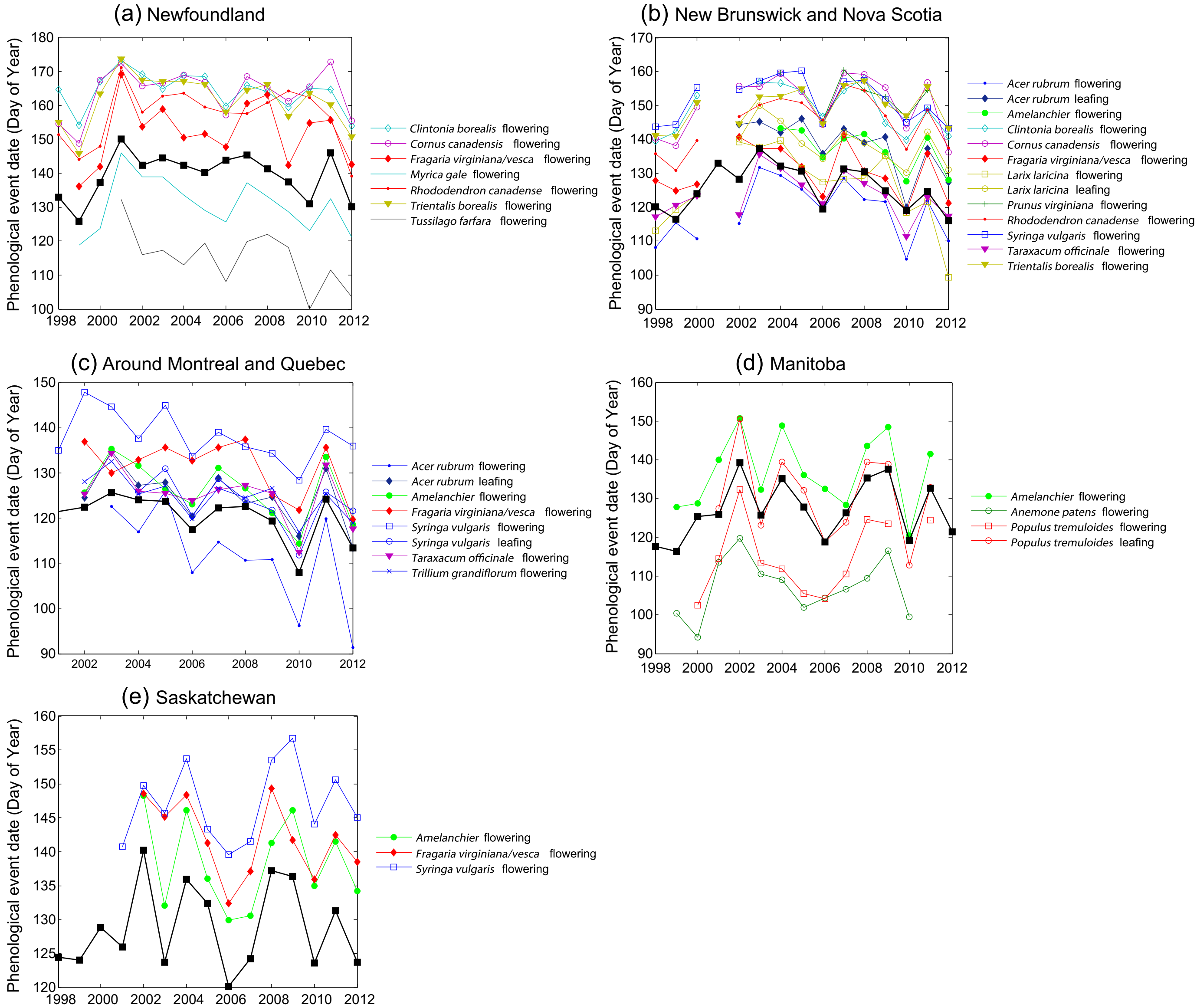

Fig. 4. Time series of phenological events (first flowering and leaf out) and of remote sensing green-up dates (black squares), aggregated at a regional level. From (a) to (e): Newfoundland, New Brunswick–Nova Scotia, South Quebec, South Manitoba, South Saskatchewan. Only the time series that are correlated with remote sensing green-up at $p < 0.01$ are shown. All results are shown in Table 4.

2011), but our validation exercise included a much larger dataset and area than these two studies.

At the regional level the timing of green-up is clearly related to variations in the leafing and flowering timing of several species. This is explained by at least two reasons that might hold simultaneously. First, bud swelling leading to leaf flushing or to flower blooming of all species may influence the remote sensing signal, each species influence depending on its abundance that varies from one pixel to the other. For example, for *P. tremuloides*, female trees develop long green catkins for a one to two week period before leaf-out which may influence the remote sensing signal. Second, spring phenology, *i.e.* the timing of leaf-out and flower blooming of many species, occurs in response to a seasonal increase in temperature, thus green-up can correlate even with a non-abundant species. Altogether the results show that green-up is sensitive to a cohort of species and events, regardless whether they are native or introduced, which plainly justifies the term of 'land surface phenology'. However it remains difficult to exploit this satellite-derived information to replace the *in situ* observations, because the agreement with a particular species changes from one region to the other. For example, we have a strong correlation for some events like *P. tremuloides* leafing in the central part of Canada, but no correlation for the same event in New Brunswick–Nova Scotia, where high correlation is found with a non-woody species (*T. officinale*) flowering. A few species (*e.g.*: flowering of *Amelanchier* spp., *C. canadensis*, *F. virginiana/vesca* or *T. officinale*) flowering is correlated in all the tested regions.

Advantages of using remote sensing rather than ground observations to study phenology include the larger spatial extent, as *in situ* observations are carried out for a relatively small fraction of Canada's territory. As well, the remote sensing measurement protocol is homogenous spatially and temporally over a period that is longer than a decade. In under-reported regions in Canada, we may expect that green-up is easily correlated with the locally present species' leaf-out and flowering, as in those wilder and less populated areas agriculture is not dominant. However the many lakes in the forest and tundra regions may disturb the detection as we have learnt (Fig. 2). Outside Canada, systematic ground observations are scarce, and some long-

Table 4
Correlation between remote sensing green-up and phenological event time series at the regional level. 0: not correlated; 1: correlated at $p < 0.05$; 2: correlated at $p < 0.001$. Flowering refers to timing of first flower.

	Newfoundland	New Brunswick/Nova Scotia	Montreal Quebec	Manitoba	Saskatchewan
Acer rubrum flowering	0	2	2		
Acer rubrum leafing	0	1	2		
Amelanchier flowering		2	2	2	
Anemone patens flowering				1	0
Clintonia borealis flowering	1	2			
Cornus canadensis flowering	2	2			
Elaeagnus commutata flowering					1
Epigaea repens flowering		1			
Forsythia suspensa flowering		0			
Fragaria virginiana/vesca flowering	1	2	1		1
Galium boreale flowering					0
Houstonia caerulea flowering		0			
Larix laricina flowering	1	2			0
Larix laricina leafing	1	2	0		
Maianthemum stellatum flowering					0
Myrica gale flowering	2				
Populus tremuloides flowering		0	1	1	1
Populus tremuloides leafing		0		2	1
Prunus virginiana flowering		1			1
Rhododendron canadense flowering	1	2			
Rhododendron groenlandicum flowering	0	1			
Syringa vulgaris flowering	0	2	1	0	1
Syringa vulgaris leafing	0	0	1		1
Taraxacum officinale flowering	1	2	2	1	0
Trientalis borealis flowering	2	1			
Trillium grandiflorum flowering			2		
Tussilago farfara flowering	2	1			
Vaccinium vitis-idaea flowering	0	2			

term networks have stopped acquiring data, like in the former Soviet Union, or in most European phenology gardens. Some newly established networks (Schwartz, 2013) have the issue that most sites are observed over a small number of years. Since citizen networks rely on the addition of individual initiatives, observation series are often short or incomplete and need spatial aggregation to allow monitoring interannual variations. Nevertheless these networks allow analysis of interspecific and intraspecific variation, which is not possible with remote sensing green-up at the spatial resolution of SPOT-VGT. Maintaining both *in situ* and satellite observations offers unique opportunities to study the evolution of plant leafing and flowering phenology in view of land surface phenology. In particular, potential mismatch between these events, resulting from climate change or land use change, may have important impact on ecological webs. Therefore initiatives like PlantWatch need to be expanded to continue the temporal record.

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