

Monitoring Recent Afforestation Interventions as Relevant Issue for Urban Planning

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Abstract. In the UN Decade on restoration, urban and peri-urban areas are increasingly recognized as key to implement afforestation interventions, thus contributing to supporting ecosystem services provision.

Nevertheless, the relation between the current vegetation health and typologies of Land Use/Land Cover (LULC) and related changes is still poorly explored, thus affecting ecosystem planning. Therefore, this study aims to investigate, through the employment of Normalized Difference Vegetation Index (NDVI), the vegetations' health in i) unchanged forest ii) afforested areas - considering the different LULC classes in which afforestation occurred iii) unchanged LULC classes in the surrounding of afforested areas; in the case study area of the Metropolitan City of Milan.

We first analyze the LULC transformation aimed at identifying unchanged forest (1954–2018), recent afforested areas (2012–2018), and the unchanged LULC surrounding the afforested areas (2012–2018) i.e., being the same LULC that preceded the afforestation process. We then analyzed Sentinel-2 NDVI sequences (2017–2023) in these three LULC transformation/unchanged categories, respectively.

The results show lower NDVI values in afforested areas transformed from impervious soil and arable lands into forest. Moreover, the results of the Wilcoxon test indicate that the average NDVI values of recently afforested areas from impervious soil, arable lands and pastures are statistically different from those of unchanged forest.

Results can be used to set an environmental benchmark for afforestation processes providing a basis in the selection of future planning priorities.

Keywords: Restoration Ecology · Land Use/Land Cover Change · Ecosystem services

This article has been inspired by the first, preliminary, analytical assessment we developed in the "National Biodiversity Future Center - NBFC" – SPOKE 5 Urban Biodiversity - CUP: D43C22001250001 – funded by the European Union - Next Generation EU under the PNRR MUR Program - "Mission 4, Component 2, Investment 1.4" - Project Code CN_000033.

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O. Gervasi et al. (Eds.): ICCSA 2023 Workshops, LNCS 14106, pp. 578–595, 2023.
https://doi.org/10.1007/978-3-031-37111-0_40

1 Increasing Importance of Afforestation Intervention in Urban and Peri-Urban Environments

Arresting and reversing the ecosystem degradation and loss of biodiversity, under the United Nation Decade on Ecosystem restoration 2021–2030, is an overarching worldwide goal [1]. At EU scale, the commitment to reach this goal was strengthened by the EU Green deal [2], EU Biodiversity strategy for 2030 [3] and, more recently, the EC proposal for a Nature restoration law [4]. Within this framework, the restoration ecology as "the process assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" [5] increases the overall resilience of the urban and peri-urban areas, also limiting adverse impacts of climate change in cities [6]. More specifically, the active restoration through e.g., the implementation of afforestation interventions [7], if planned and designed considering the ecosystems complexity and diversity [8], lead to restore ecosystems enhancing the related services, such as biodiversity, carbon storage and sequestration [9], heat and urban flood risk mitigation [10, 11], thus contributing to reduce the vulnerability of communities against climate risks [12]. In an effort to improve such benefits, the mapping and assessment of the Ecosystem Services (ES) provision related to different Land Use/Land Cover (LULC) is crucial as LULC affects e.g., the quality of habitats [13], and the LULC transformation impacts on different ecosystem services provision [14]. The afforestation process is one of the major LULC transformations worldwide [15] and policies and programs, as already mentioned, are supporting such interventions globally for increasing the ES provision and improving the biodiversity and the quality of habitat. However, monitoring such afforestation interventions within the overall umbrella of active restoration is key, since it is commonly assumed that afforestation should tend to have the same dynamics and complexity as natural ecosystems to be considered successful [14] and the incomplete recovery is often due to scarce understanding of the LULC and its transformation [16]. So far, several researchers analyzed the combination of spatial change of LULC and Normalized Difference Vegetation Index (NDVI) time series to assess e.g. the modification of vegetation cover and its implication for degradation monitoring in semi-arid environments [17, 18] or the negative impact of urban development on natural ecosystems [19]. NDVI is a key indicator usually employed to assess a wide range of ES including the habitat-supporting services (according to the Millennium Ecosystem Assessment (2005) classification [20]) [21, 22].

However, the relevance of the type of LULC on which the afforestation intervention has placed and the current vegetation health of such afforestation intervention is still poorly explored resulting in limited information to support urban planning in selecting the priorities of intervention in the next future. Thus, within these limits, further efforts are needed to monitor the current, and better target the future, afforestation interventions in urban and peri-urban areas aiming at increase related ecosystem services provision.

Based on the above-mentioned issues, this study aims at analyzing the vegetation heath of forest and recent afforestation interventions occurred in the Metropolitan City of Milan comparing the NDVI values, as proxy of vegetation's health status, considering in particular: i) unchanged forest as reference state (1954–2018); ii) recent afforested areas from different LULC (2012–2018); ii) unchanged LULC in the surroundings of afforested areas (2012–2018).

2 Materials and Methods

2.1 Case Study Area

The Metropolitan City of Milan (MCM) is located in Lombardy region, covers about 157,565 ha and is mainly dominated by arable lands (68,291 ha) and impervious soil[1] (55,525 ha). Artificial, non-agricultural vegetated areas (9,322 ha), pastures (7,123 ha), shrublands and open spaces with little or no vegetation (2,531 ha) and forest (10,308 ha) as well as wetlands (108 ha) are scattered throughout the plain, fertile land. Larger wooded lands, dominated by broadleaf forest, are mainly located in the Ticino riparian zone and in the north and north-west part of the MCM (Fig. 1).

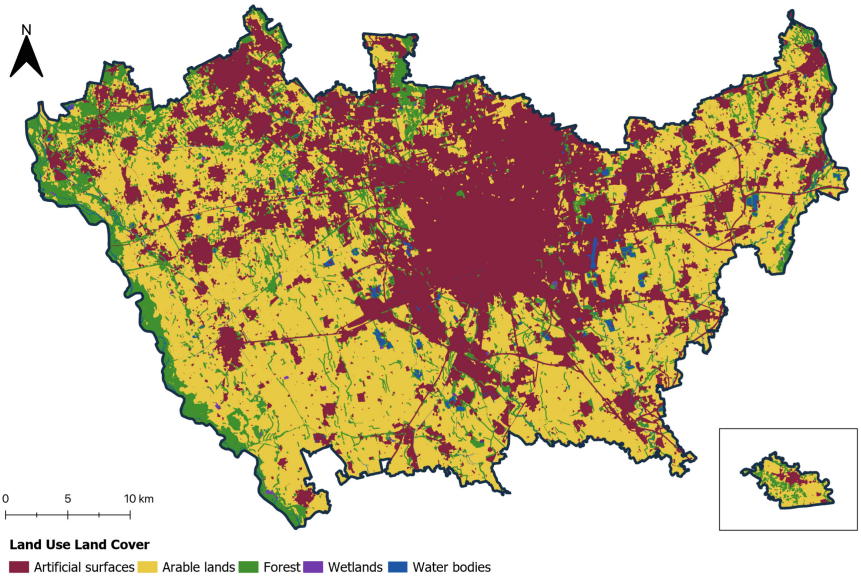

Fig. 1. Map of the main LULC classes in MCM in 2018. Data elaborated from DUSAF (Destinazione d'Uso dei Suoli Agricoli e Forestali) database, ERSAF Lombardy region (https://www.geoportale.regione.lombardia.it/).

2.2 Land Use/Land Cover Change Classification

We first reclassify LULC of MCM into categories of interest for this study. Through the Geoportal of Lombardy region[2], the Land Use/Land Cover database (DUSAF) was downloaded and used as input to identify:

i) unchanged forest (1954–2018);

[1] In the present article we define as impervious soil the areas belonging to the classes 1.1, 1.2, 1.3 of CORINE Land Cover, within the macro-class "1. Artificial surfaces", to differentiate these to the class "1.4 Artificial, non-agricultural vegetated areas".

[2] https://www.geoportale.regione.lombardia.it/.

ii) recent afforested areas, i.e., areas transformed from other LULC (2012) to forest (2018);
iii) unchanged LULC - non-afforested areas, i.e., areas in the surroundings of afforested areas that have not changed LULC (2012–2018).

The Land Use/Land Cover dataset (DUSAF) is freely downloadable and available for the years 1954, 1980, 1999, 2007 and 2018 and the first three levels of LULC classification are consistent with the EU Copernicus CORINE Land Cover legend[3].

The vector data for the reference years 1954, 2012, 2018 were first converted into a raster with a resolution of 5m. Each pixel was then reclassified according to Table 1. In particular, three main types of areas were identified:

i) unchanged forest (called FOR-FOR in Table 1): forest in both years 1954 and 2018. To reduce the number of classes, broad-leaved and mixed forests were joined, no coniferous forest was identified in MCM;

   FOR-FOR class was used as reference state to assess differences in values between historic ecosystems (i.e. unchanged forest) [23], and recent afforested areas;
ii) recent afforested areas (namely IMP-FOR, UGA-FOR, ARA-FOR, PRM-FOR, PAS-FOR and SHR-FOR in Table 1): other LULC classes in 2012 that belonged to forest in 2018. Areas converted from wetlands (class 4) and water bodies (class 5) were not considered in the present study due to their very small coverage comparing to the whole MCM;
iii) unchanged LULC - non-afforested areas, i.e., other LULC within 1 km distance from the recent afforested areas whose, in contrast to the latter, maintained the same LULC in 2012 and 2018 (called IMP-IMP, UGA-UGA, ARA-ARA, PRM-PRM, PAS-PAS, SHR-SHR in Table 1). These areas were used to assess the differences, if any, between the afforested areas and their surroundings.

We re-classified the dataset obtaining a single-band raster whose pixel's value corresponds to every detected change. The raster image was then converted into a shapefile containing a polygon for each group of adjacent pixels belonging to the same type of LULC change class. Resulting polygons smaller than 0.1 hectares have then been removed from the datasets, since they may have been artifacts resulted from rasterization and inconsistencies of photo-interpretation between different years.

2.3 Computation of NDVI

In previous studies, indicators calculated from surface reflectance values obtained from satellite measurements have been successfully used to assess and monitor vegetation health [24–26]. The use of satellite imagery has the advantage of covering large areas with continuous monitoring, which would be costly with in-situ measurements. To assess significant differences between unchanged forest, recently afforested areas and different types of unchanged LULC in the surrounding of afforested areas, we used the NDVI

[3] https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html.

Table 1. Reclassification of Land Use/Land Cover (LULC) considering: i) unchanged forests (1954–2018), ii) afforested areas (2012–2018) and iii) unchanged LULC – non-afforested areas (2012–2018). Per each type of classification, the LULC classes in 1954, 2012 and 2018 (for further information about classes please see https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html), the related Type of conversion from a LULC to another and the Abbreviation are reported.

Unchanged forest (1954–2018)			
LULC class in 1954	**LULC class in 2018**	**Type of conversion**	**Abbreviation**
311, 312, 313	311, 312, 313	From "Forest" to "Forest"	FOR-FOR
Afforested areas (2012–2018)			
LULC class in 2012	**LULC class in 2018**	**Type of conversion**	**Abbreviation**
11, 12, 13	311, 312, 313	From "Impervious soil" to "Forest"	IMP-FOR
14	311, 312, 313	From "Artificial, non-agricultural vegetated areas" to "Forest"	UGA-FOR
21	311, 312, 313	From "Arable lands" to "Forest"	ARA-FOR
22	311, 312, 313	From "Permanent crops" to "Forest"	PRM-FOR
23	311, 312, 313	From "Pastures" to "Forest"	PAS-FOR
32, 33	311, 312, 313	From "Shrublands and open spaces with little or no vegetation" to "Forest"	SHR-FOR
Unchanged LULC – non-afforested areas (2012–2018)			
LULC class in 2012	**LULC class in 2018**	**Type of conversion**	**Abbreviation**
11, 12, 13	11, 12, 13	From "Impervious soil" to "Impervious soil"	IMP-IMP
14	14	From "Artificial, non-agricultural vegetated areas" to "Artificial, non-agricultural vegetated areas"	UGA-UGA
21	21	From "Arable lands" to "Arable lands"	ARA-ARA
22	22	From "Permanent crops" to "Permanent crops"	PRM-PRM
23	23	From "Pastures" to "Pastures"	PAS-PAS

(*continued*)

Table 1. (*continued*)

32, 33	32, 33	From "Shrublands and open spaces with little or no vegetation" to "Shrublands and open spaces with little or no vegetation"	SHR-SHR

[27] (Formula (1)).

$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}} \quad (1)$$

where NIR is the reflection in the near-infrared spectrum and RED is the reflection in the red range of the visible spectrum. The NDVI is employed for examining the vitality of plants by capturing the amount of light absorbed and reflected by available chlorophyll [28]. The value range of the NDVI is -1 to $+1$. NDVI negative values correspond to water; values close to 0 are typical of barren soils or vegetation at the beginning and the end of the growing season; low positive values correspond to shrub and grassland and high values correspond to temperate and tropical rainforests with highest greenness [24].

NDVI values were computed by Sentinel 2 multispectral imagery collections with high spatial and temporal resolution (10m images related to bands 8 and 4, required for NDVI computation, are provided every 5 days). Using the Google Earth Engine platform, we retrieved already atmospherically corrected Sentinel 2 L-2 surface reflectance images from May 2017 onwards (March 2023). Only images with less than 40% cloud cover were selected. We computed the NDVI value for each image after masking clouds present in the scenes. After this, we computed monthly average NDVI images, which were then mosaicked to cover the MCM.

For each polygon resulting from the reclassification of LULC change, we computed an average monthly NDVI time series by calculating, over the area covered by the polygon, the average value of the monthly NDVI obtained from the processing of the Sentinel 2 images. At the end of the process, we obtained a monthly NDVI time series for each single polygon related to unchanged forest and afforested areas (i.e., related to classes FOR-FOR and IMP-FOR, UGA-FOR, ARA-FOR, PRM-FOR, PAS-FOR, SHR-FOR), containing an NDVI average value per each month from May 2017 to March 2023. It should be noted that non-forested areas with an unchanged LULC (i.e., classes IMP-IMP, UGA-UGA, ARA-ARA, PRM-PRM, PAS-PAS, SHR-SHR) were considered as a single polygon and therefore a single NDVI time series was generated for the whole unchanged area.

2.4 Statistical Analysis

A yearly NDVI shape was produced for each polygon by averaging NDVI values related to each month of the year (e.g., May-2017, May-2018, May-2022). Finally, a single yearly NDVI shape was computed for each category of LULC change defined in Table 1.

We assumed that there are differences in the NDVI average values in unchanged forest, recently afforested areas and unchanged LULC in the surrounding of afforested areas. To compare these three categories, we computed maximum, minimum and average NDVI values. On this basis, we performed the Wilcoxon test [29] to compare NDVI average values of unchanged forest and recently afforested areas assessing whether there are significant differences between the state of health of afforested areas and the one in unchanged forest as reference state.

3 Results

3.1 Land Use/Land Cover Change Classification

The reclassification identified 4,337 ha of unchanged forest (about 3% of MCM). Considering the LULC change, a total of 1,142 ha was converted from impervious soil, artificial, non-agricultural vegetated areas (i.e., urban green areas), arable lands, permanent crops, pastures and shrublands and open spaces with little or no vegetation, to forest. The conversion from arable lands to forest (ARA-FOR) is the class with the highest extent area that have been transformed, followed by the conversion of shrublands and open spaces with little or no vegetation (SHR-FOR), pastures (PAS-FOR), artificial, non-agricultural vegetated areas (UGA-FOR), permanent crops (PRM-FOR), impervious soil (IMP-FOR) to forest (see Table 2). The arable lands, pastures and permanent crops classes make the 57% of the total of recently afforested area, implying that most of afforestation process in MCM occurs at the expense of agricultural areas. On the contrary, the conversion of impervious soil to forest makes about only 8% of the total of recently afforested area.

Figure 2 and Table 2 show the result of reclassification.

Table 2. The unchanged forest and different afforested areas (class), the related hectares (area (ha)), the count of polygons referred to each class (count) and the average polygon extent in ha (avg area) are reported. Refer to Table 1 for abbreviations of afforested areas.

Unchanged forest (1954–2018)			
class	**area (ha)**	**count**	**avg area**
FOR-FOR	4,337.75	1052	4.12
Afforested areas (2012–2018)			
class	**area (ha)**	**count**	**avg area**
IMP-FOR	88.93	200	0.44
UGA-FOR	111.47	105	1.06
ARA-FOR	367.03	726	0.51
PRM-FOR	96.86	95	1.02
PAS-FOR	190.47	407	0.47
SHR-FOR	287.64	303	0.95

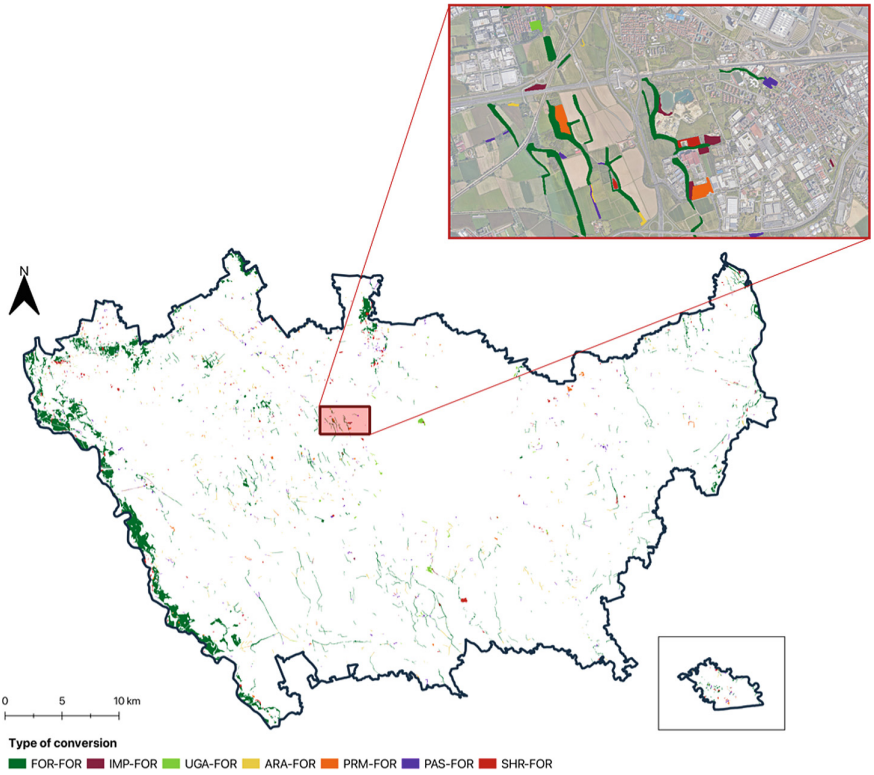

Fig. 2. Map of the unchanged forest (1954–2018) and LULC transformation due to recent afforestation process (2012–2018) occurred in MCM. Data elaborated from DUSAF (Destinazione d'Uso dei Suoli Agricoli e Forestali) database, ERSAF Lombardy region (https://www.geoportale.regione.lombardia.it/).

3.2 NDVI Values

As earlier mentioned, for each area identified through reclassification, the yearly mean values of NDVI have been computed. The main results are summarized in Table 3. In detail, the transformation of impervious soil to forest is the conversion class with the lowest mean NDVI values (mean value < 0.6). Instead, the conversion of pastures (PAS-FOR) and permanent crops (PRM-FOR) to forests are the classes with highest mean NDVI values (mean value 0.655 and 0.658, respectively).

According to the Wilcoxon test results, only 3 classes of afforested areas showed statistically significant difference ($p < 0.001$) with unchanged forest values, i.e., conversion of impervious soil (IMP-FOR), arable lands (ARA-FOR) and pastures (PAS-FOR) to forest.

Table 3. Per each unchanged forest and different afforested areas classes, the mean NDVI, the standard deviation (sd NDVI), the maximum and minimum values and the related range (max NDVI, min NDVI, range (max-min)) and the p-value are reported. Refer to Table 1 for abbreviations of afforested areas.

Unchanged forest (1954–2018)						
class	**mean NDVI**	**sd NDVI**	**max NDVI**	**min NDVI**	**range (max-min)**	**p-value (NDVI year)**
FOR-FOR	0.648	0.052	0.785	0.438	0.346	NA
Afforested areas (2012–2018)						
class	**mean NDVI**	**sd NDVI**	**max NDVI**	**min NDVI**	**range (max-min)**	**p-value (NDVI year)**
IMP-FOR	0.588	0.079	0.716	0.397	0.319	<0.001
UGA-FOR	0.626	0.072	0.765	0.427	0.338	0.0053
ARA-FOR	0.620	0.057	0.738	0.440	0.299	<0.001
PRM-FOR	0.658	0.050	0.806	0.456	0.351	0.0544
PAS-FOR	0.655	0.062	0.776	0.465	0.311	<0.001
SHR-FOR	0.649	0.064	0.799	0.430	0.369	0.1130

The analysis of NDVI in afforested areas, i.e., areas transformed from other LULC (2012) to forest (2018), shows that, on average, the cold and growing seasons are very similar in almost all the afforested areas from different LULC classes (i.e., IMP-FOR, UGA-FOR, ARA-FOR, PRM-FOR, PAS-FOR, SHR-FOR) compared to the NDVI trend of the unchanged forests (FOR-FOR). From March, corresponding to the beginning of the growing season, NDVI starts to increase reaching a peak in May for afforested areas from permanent crops, shrublands, pastures, urban green areas and impervious soil; instead, the time of maximum greenness of afforested areas from arable lands varied between June and August, as in the case of unchanged forests.

The highest average NDVI values (maximum greenness) are reached in afforested areas from permanent crops (0.658), slightly lower in pastures (0.655), shrublands (0.649) and unchanged forest (0.648). The afforested areas from the impervious soil class have the lowest NDVI value in every month and on average (0.588).

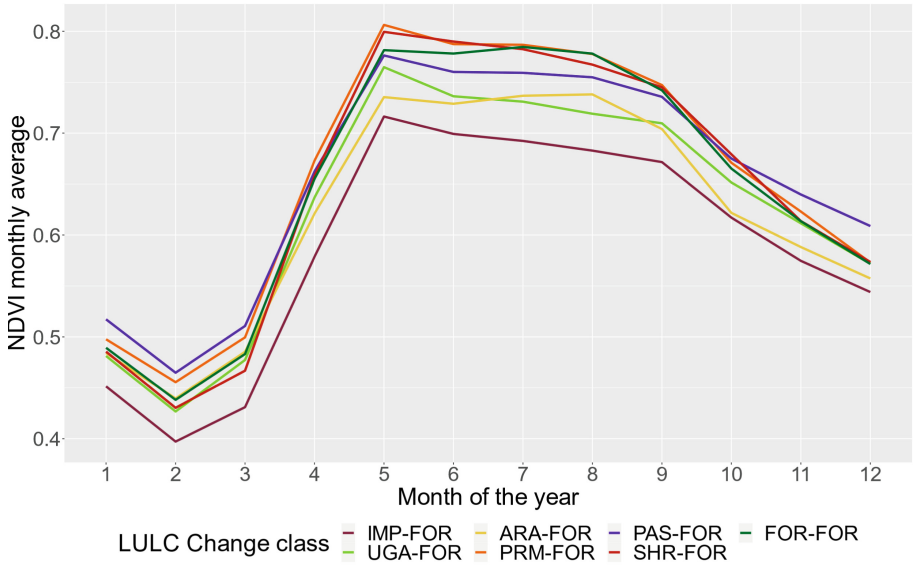

Fig. 3. Seasonality of NDVI values (average) in unchanged forest (FOR-FOR) and afforested areas from different LULC. Refer to Table 1 for abbreviations of afforested areas.

3.3 NDVI Comparison Between Afforested Areas and Unchanged LULC in the Surrounding

Table 4 and Fig. 4 show a comparison between areas that have been recently afforested with areas in their surrounding (within 1 km distance) which, in contrast to the afforested areas, maintained the same LULC in 2012 and 2018.

There are differences in NDVI increasing between afforested classes. The conversion from impervious soil to forest (IMP-FOR) reports the highest NDVI increment (0.29), followed by shrubland (SHR-FOR, 0.13) and then arable lands (ARA-FOR, 0.12) to forest. The lowest average increment is referred to the conversion of artificial, non-agricultural vegetated areas (UGA-FOR, 0.06), i.e., urban green areas, and permanent crops (PRM-FOR, 0.05) into forest; the gain is concentrated in months from May to September while for winter months values are similar. On the contrary, the conversion of pastures to forest (PAS-FOR) implies an NDVI decrease (−0.03). Considering the average maximum NDVI, the difference of IMP-FOR is even higher, reaching average value of 0.38. Instead, the difference in NDVI values between afforested areas and the unchanged LULC in surrounding of them are not relevant.

Table 4. Afforested areas from different types of LULC (rows) and related NDVI average and maximum values and the difference between the maximum and minimum NDVI values are reported (affor. columns) as well as NDVI average and maximum values of the unchanged LULC surrounding the afforested areas and the difference between the maximum and minimum NDVI value (ref. columns). The difference between afforested areas NDVI values and those related to unchanged LULC surrounding afforested areas are also included (delta columns).

	ref. LULC meanNDVI	**affor.meanNDVI**	**deltameanNDVI**	**ref. LULC max NDVI**	**affor.max NDVI**	**deltamax NDVI**	**ref. LULC rangeNDVI(max-min)**	**affor. RangeNDVI (max-min)**	**delta rangeNDVI (max-min)**
IMP-FOR	0.29	0.59	0.29	0.33	0.72	0.38	0.09	0.32	0.23
UGA-FOR	0.57	0.63	0.06	0.65	0.76	0.11	0.19	0.34	0.15
ARA-FOR	0.50	0.62	0.12	0.66	0.74	0.08	0.26	0.30	0.04
PRM-FOR	0.61	0.66	0.05	0.69	0.81	0.11	0.19	0.35	0.16
PAS-FOR	0.69	0.66	− 0.03	0.75	0.78	0.03	0.15	0.31	0.16
SHR-FOR	0.52	0.65	0.13	0.63	0.80	0.17	0.28	0.37	0.09

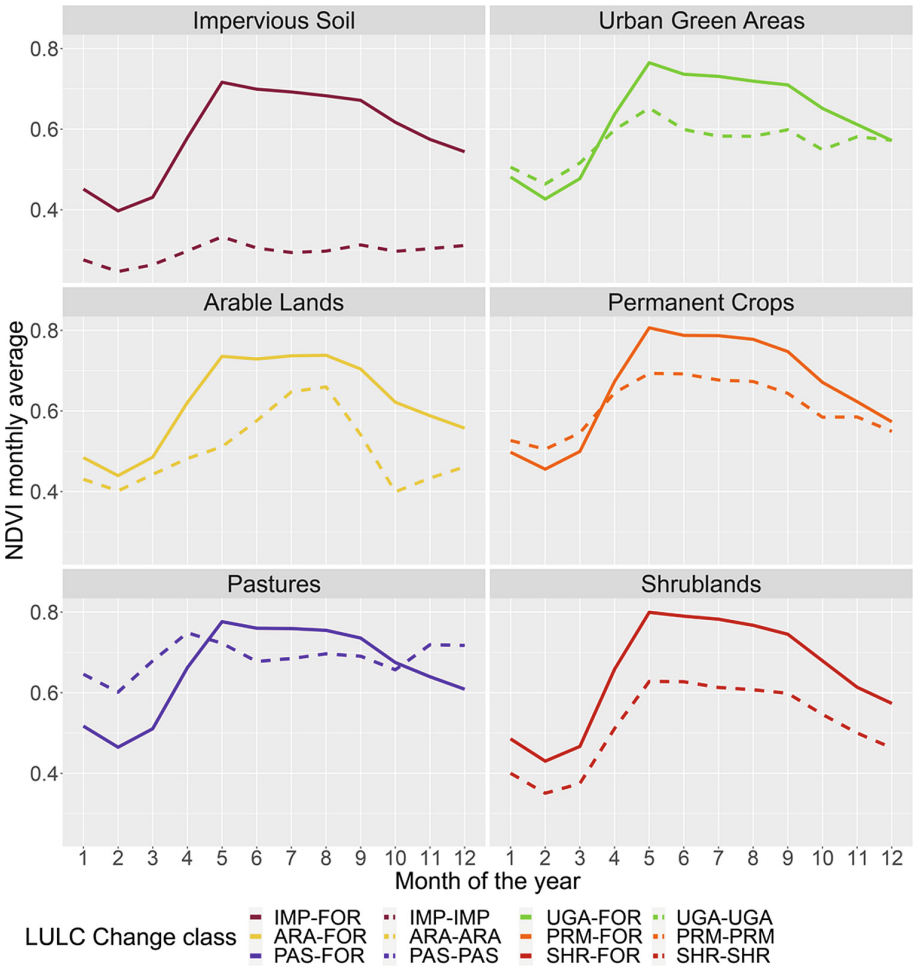

Fig. 4. NDVI trends in afforested areas originated from impervious soil (IMP-FOR), artificial, non-agricultural vegetated areas (UGA-FOR), arable lands (ARA-FOR), permanent crops (PRM-FOR), pastures (PAS-FOR) and shrublands (SHR-FOR) are reported (continuous line) in the same box with NDVI trends in the areas in the surroundings of afforested areas that have not changed LULC (dashed line). Refer to Table 1 for abbreviations of afforested areas.

4 Discussion and Conclusion

We tested our hypothesis to assess different vegetation states of health conditions in unchanged forest (1954–2018), recent afforested areas (transformed from other LULC (2012) to forest (2018)), and with unchanged LULC in the surroundings of afforested areas (2012–2018).

Although it could be reductive to compare two LULC solely on NDVI values, this study is the first attempt to analyze afforestation interventions, which should aim to have the same dynamics as natural ecosystems to be considered successful [14], and the

unchanged forests as the reference state. The Wilcoxon test results allow us to distinguish two groups of afforested areas (Table 3):

I) the group of afforested areas from different LULC with NDVI average values significantly different from that of unchanged forest;
II) the group of afforested areas from different LULC with NDVI average values similar to that of unchanged forests.

In detail, afforested areas from arable lands and impervious soil have statistically different mean NDVI values from unchanged forests. This is probably due to the intensive management of arable lands, which is correlated with low values of root length [30] and which, in turn, affects the vegetation growth [31]. Indeed, considering the effects on root length, LULC types are more important than site conditions [30]. The same can be applied to afforested areas from impervious soils. Instead, afforested areas from artificial non-agricultural vegetated areas, i.e., urban green areas, have similar NDVI values to unchanged forests, thus in line with studies in the literature [30] as well as permanent crops and shrublands.

Considering the average NDVI values change between the unchanged LULC classes in the surrounding of afforested areas and the recent afforested areas (Table 4, Fig. 4), the highest increase in NDVI values is related to the impervious soil to forest transformation mainly due to the greenness variation. The pastures, as unchanged LULC, present higher value in the cold season than afforested areas originated from them. The shrublands and afforested areas originated from shrublands maintain the same trend of NDVI average values in the year, as have a phenological behavior similar to the one of trees [32].

According to the results, particular attention should be paid to monitoring the afforestation intervention in impervious soil and arable lands, being the categories that differ most from unchanged forest considered the average values of NDVI.

4.1 Connection of LULC Transformations, Vegetation Health and Urban Planning

The article demonstrated the validity of this approach to heuristically define the characteristics of the afforestation process through threshold analysis. At the same time, this method can pave the way for further studies in other geographical and climatic contexts that can employ a similar process and verify abrupt changes in this index and check them by field survey. As the NDVI is a seasonal indicator which is affected by climate-driving factors [33] and the vegetation growth is related to diverse vegetation and climate characteristics [34], the exact definition of common threshold values used in different cases is not fixed. Even though other authors have already practiced this approach for different scopes [35, 36], we can confirm that NDVI trend analysis can be used for a relatively short-time monitoring aimed at verifying the human-induced changes in the landscape and supporting the decision-making for urban planning.

For example, as the NDVI has a positive correlation with vegetation biomass [37] and productivity [38] and different ecosystem services such as water yield, soil conservation, carbon storage and food supply [39], the results of the present study lay the basis for future planning scenarios aimed at increase ecosystem services. Thus, according to the main findings, in an afforestation scenario priority should be given to transforming

impervious soil and arable lands to forest with the main goal of increasing the greenness and vegetation health status of such areas. As highlighted by the research outcomes, reducing the anthropic footprint can be considered the most radical and tangible solution to potentially increase biodiversity, as land cover and NDVI are predictors of e.g. habitat selection along migration [40].

The NDVI variation between impervious soil to forested areas shows a gain which doubles the second highest transition typology: from shrublands to forest. This empirical evaluation has a strong policy implication since it confirms that urban greening policies aimed at changing impermeable to permeable surfaces can maximize many ecological benefits, e.g., restoring the biological quality and fertility of soil [41]. New permeable areas should replace the existing sealed areas to improve biodiversity performance and create ecological continuity among the main core natural areas internal and external to the urban fringe while fostering ecological connectivity and slow mobility. Detailed interventions can enhance de-sealing processes to improve water infiltration, reduce run-off, and increase water retention [42] in new afforested areas. Permeable pavements can substitute traditional asphalt with pervious concrete or interlocking and plastic grid pavers. These solutions are particularly effective in reducing surface run-off while augmenting evapotranspiration [43]. Besides, over the infiltration process, semi-permeable material allows higher evapotranspiration while filtering and storing rainwater [44].

Also, abrupt changes in the mean NDVI are observed in the transition from arable lands to forest. This specific transition is highly favorable for reducing climate change effects induced by intensive land exploitation due to agricultural production. Even though there is a huge trade-off between crop production and biodiversity [45], the re-naturalization of former agricultural land into forest can highly augment the nutrient retention in the soil particularly in the 10-year-old afforestation compared to 60–70 years-old-ones [46] augmenting carbon sequestration and biodiversity consequently. However, on the one hand, attention should be paid to improve soil conditions during the site preparation before tree and shrub plantings to support urban afforestation in increasing soil carbon concentrations, water holding capacity and nutrient retention, among others benefits [47]. This could limit the difference in average NDVI values between impervious soil and arable lands and shrublands (see Table 3). On the other hand, despite the considerable increase in the average NDVI value from arable lands to forest, it is worth considering that large scale afforestation occurs on arable or abandoned agricultural lands could have displacement effects elsewhere, such as deforestation, due to the import of agricultural crops and livestock [48].

Thus, it is crucial to plan in a targeted way, limiting the large-scale transformations, generally prioritizing the impervious soil transformation to forest and detailed afforestation interventions on other LULC considering the results of the present study and the inclusion of afforested areas in a broader urban and landscape planning aimed to restore ecosystems and enhance the related services.

4.2 Limitations

This study introduced a novel approach to monitor NDVI trends for specific LULC transformations. Specifically, yearly NDVI trends on afforested areas were compared to check whether it is possible to reach the same NDVI levels of unchanged forests. This

research question has been positively answered only for specific kinds of transitions, while not for others. However, the main limitations of this approach are: i) the lack of current and/or previous study on this subject that could be considered as an initial thresholds for an area subjected to naturalization process; ii) the reduced time-series of NDVI observation 2017–2023 that may not be sufficient to track the evolution of biodiversity increase during and after the afforestation process and, finally, iii) some intrinsic issue of NDVI data that make it a partial, seasonal and limited indicator whose employment is restricted to detect vegetation health status and not biodiversity assessment. We are aware that in this work we use NDVI as a proxy of vegetation performance which could be included in biodiversity modelling, however we cannot consider the empirical evaluation of NDVI as an assessment of biodiversity, since much more detailed, onsite-field analysis should be put in place to empirically check if and how much the afforestation process increased the ecological biodiversity in the catchment.

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