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Evaluating the contribution of urban ecosystem services in regulating thermal comfort

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Abstract The study focuses on spatio-temporal dynamics of urban ecosystem services (UES) and their contribution in maintaining thermal comfort in Bhubaneswar city, India. An extensive increase in UES demand (grey) patches (187.95%) was observed during 1992–2016 in contrast to significant decline (47.94%) in UES supply (blue–green) patches, primarily in the northern and south–western directions. Also, a drastic rise in area under thermally highly uncomfortable zone (35–40 °C) from 0.005 to 56.68 km^2 and a decrease in area of thermally comfortable zone ($\leq$ 26 °C) from 0.46 km^2 to zero during 1992–2016 exhibiting deteriorating natural urban living condition. Although, the land surface temperature (LST) was remained higher in urban areas, the peri-urban and neighbouring rural areas (27.31–33.98 °C) of Bhubaneswar city recorded a high increase in mean LST as compared to the urban areas (31.19–34.69 °C). In both the cases, UHI intensities were less as compared to other growing cities of India. The MODIS based time series analysis depicted similar trends with minor increase in LST (30.55–30.76 °C) during 2000–16. The study proves the intrinsic linkages of UES with thermal comfort and necessitates to adopt sustainable measures to make the city green and habitable.

Keywords Urban ecosystem services · Thermal comfort · Land surface temperature · Surface urban heat island · Geoinformatics

1 Introduction

Many developing cities of the world are facing tremendous population influx and rapid urbanization leading to substantial and irreversible land use change [1, 2]. Despite this, humans still depend on nature for her products and services [3]. The extent of the dependence can be gauged by a study of the 29 largest cities in Baltic sea region, which revealed that cities required ecosystem support for its sustainability and quality of life [3]. Man-made ecosystems are considered immature, when compared to natural ecosystems due to their incompetent and inefficient use of resources such as energy and water [4]. Ecosystem is a set of interacting species with their local, non-biological environment functioning together to sustain life [5], whereas cities encompasses single or are composed of several individual ecosystems within urban environments, creating a more complex environment [6]. The benefits that people receive from ecosystems are known as ecosystem services [7, 8] which range from resources such as food, fodder to abstract services such as temperature and climatic regulation. Urban nature has been important since ancient times [9], in which green spaces were having a vital role in cities as evident through paintings and structures in the Alhambra [10]. It was in the 1990 s that experts began to address urban nature in the context of ecosystem services,

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which are often correlated with the land use/cover compositions [11].

The alteration of the natural landscape is a dominant practice on the earth surface in recent decades primarily due to urbanization to meet the increasing demands [12]. Cities are facing sprawl in fractal and are no longer compact, isodiametric aggregations [13], where the peri urban boundaries are more volatile and under maximum transition [14]. The new resultant forms of urban development including edge cities, [15] where built-up interspersed in the natural environment viz, forest, desert habitats and shrub lands [16]. These significant altering in the surrounding landscape, presents challenges in maintaining the green–blue spaces and affecting human health and well-being [17]. Analysing indicators of ecosystem help in understanding the ecological processes of an urban ecosystem [18]. Although ecosystem function is not directly benefiting the human, as compared to ecosystem services, the specific results of ecosystem functions contribute to sustaining or enhancing human life [19, 20]. Components of nature which are directly used, consumed, or enjoyed to produce human well-being should only be considered as final ecosystem services [8, 21]. There is very minimal knowledge about how densification of the urban areas leads to alteration in the natural environment [22]. These ecosystem services provided by the spaces surrounding the city may be correlated with land use/cover classes (LULC). Different LULC classes provide varied ecosystem services, depending upon the nature of the benefit it provides to the corresponding urban areas. The proper temporal and accurate change detection of the earth's landscape provides a foundation for better understanding of the interrelationships between the manmade and natural environment as well as better management of resources [23].

Urban climatology is considered as a fundamental aspect for urban planning [24, 25] since comfortable living conditions are an important criterion for modern day cities. Thermal comfort is one of the prime indicators of living conditions inside cities. It is influenced by the climatic conditions present in and around the city and is most closely related with microclimatic parameters like temperature and humidity [26]. Balanced temperature and humidity ranges are considered most suitable for optimum comfort. Also, better microclimatic conditions boost development of cities, as by controlling sources of discomfort, sedentary activities as well as mobile activities such as use of public transport, cycling, etc. are promoted [26]. Thermal comfort monitoring and description is important for constructing proper urban plans and to increase the functionality of the urban areas. Urban areas have a very different surface from that of non- urbanized and natural areas. It is usually associated with a larger extent of impervious surface and lower vegetation cover as compared to neighboring non-urbanized areas. As a result, when vegetated and evaporating soil surfaces are replaced by relatively impervious low albedo paving and building materials, there arises a temperature difference between urban and surrounding non-urban areas [27] referred to as Urban Heat Island (UHI) [28]. UHI is an attribute of urban land transformation which reflects a broad range of important land surface changes impacting human health, ecosystem function, local weather and possibly climate [27]. The alteration of temperature beyond individual comfort level has increased the dependency on artificial instruments (AC, cooler), which later induces GHG emission and further deteriorates the natural thermal environment. The present study focuses mainly on the spatio-temporal dynamics of green (forest, cropland, grassland, etc.), blue (water bodies), and grey class (built-up land) and their contribution in regulating the local and regional land surface temperature. In the present study, an attempt has been made to understand the landscape dynamics which are taking place due to urbanization and to also evaluate its relationship with ecosystem service producers and consumers.

2 Method

The study area comprised of Bhubaneswar Municipal Corporation (BMC), India and is located between 20° 11′ and 20° 23′ N latitude and 85° 43′ to 85° 56′ E longitude, at an elevation of around 45 m above MSL covering an area of 51.66 km^2 (Fig. 1). The demarcation of the study area was done considering the 2 km outer buffer of Bhubaneswar Municipal Corporation (BMC) boundary, which is the capital of Odisha state. It is also surrounded by Daya river in the south-east and Khuakhai river in the east. The city has an average annual temperature of 27.4 °C and an average annual rainfall of 1505 mm. The population in Bhubaneswar city was 837,737 persons in 2011 [29], which increased to 1163,000 persons in 2020 [30].

In the present study, various multi-temporal LANDSAT satellite data series of 1992, 2003 (LANDSAT 4,5—Thematic Mapper (TM)) and 2016 (LANDSAT 8—Operational Land surface Imager (OLI)) were used to delineate urban ecosystem services using Support Vector Machine (SVM) classification algorithm [31], which has been shown to be effective for object recognition [32–34]. The built-up land was considered as a major service consumer/demand class and referred to as grey patch/spaces (Fig. 2; Table 1). Further, vegetation cover and water were considered as major service providers/supply classes and referred as green and blue patches, respectively.

The variation in Land Surface Temperature (LST) has a direct relationship with human health and living comfort.

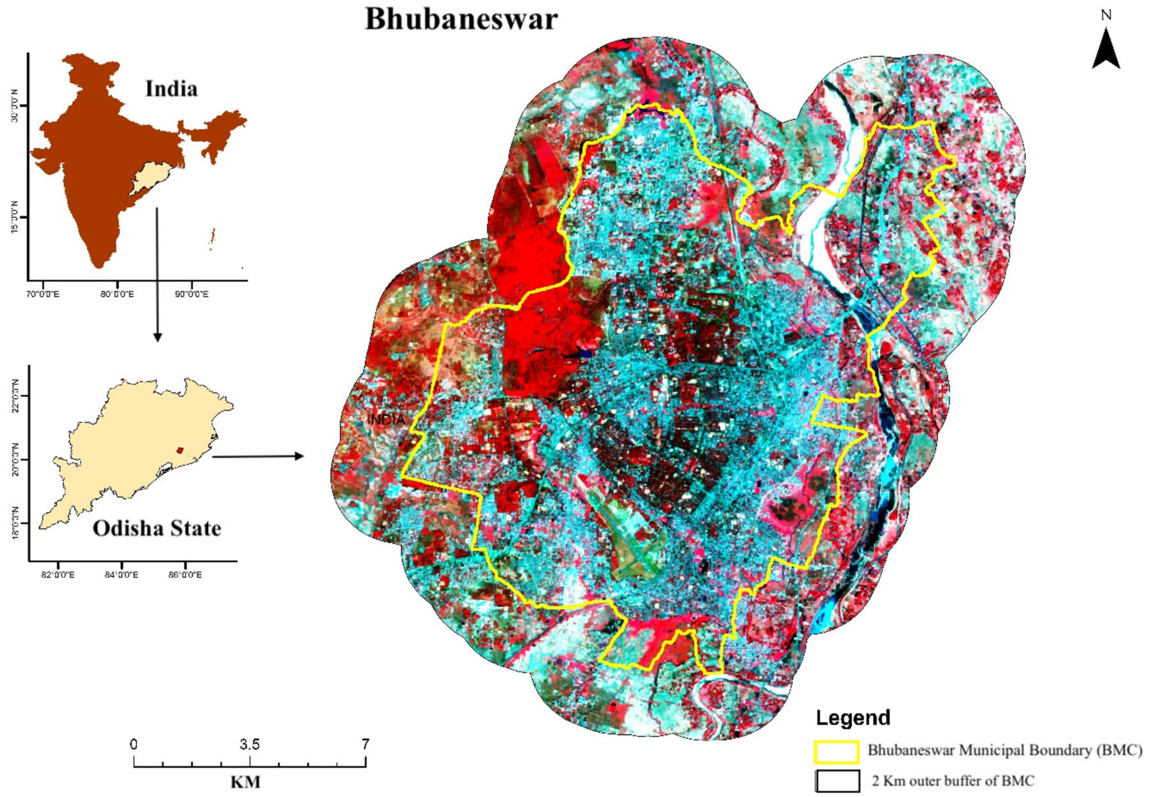

Fig. 1 Study area showing Bhubaneswar city and its peri-urban region

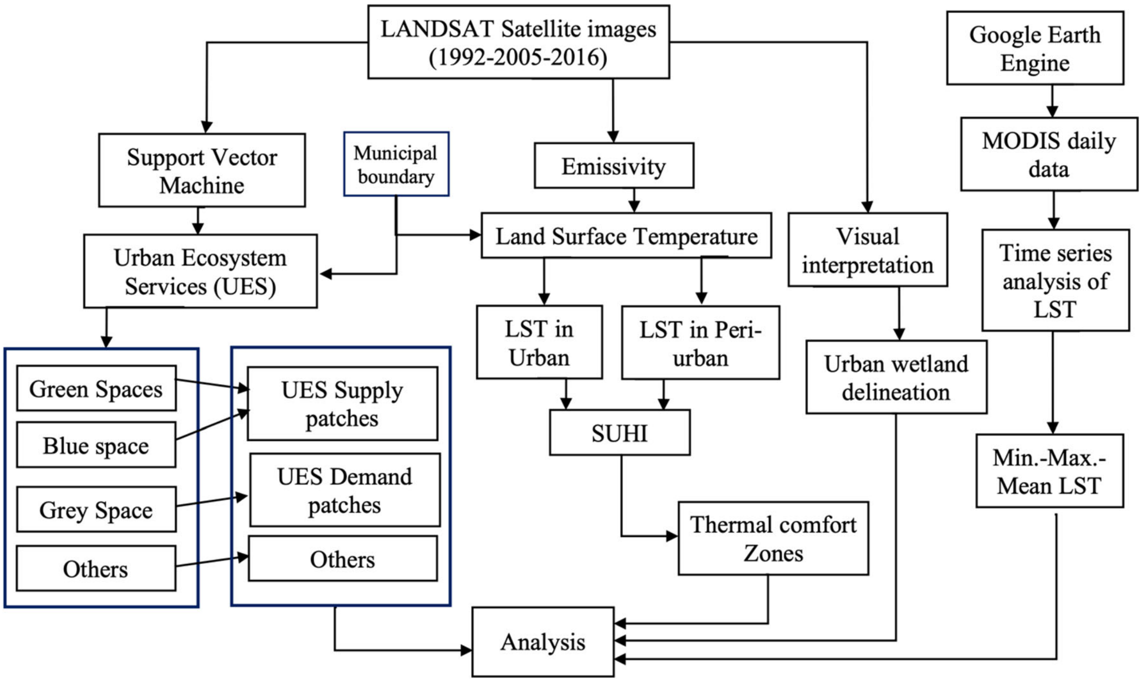

Fig. 2 Methodology flow chart

LST range between 18 and 21 °C is the most suitable temperature region for mankind and considered as most comfortable [35] and referred as thermally comfortable zones in the study. The radiance of satellite based thermal bands were converted to at-satellite brightness temperature with the help of the Eq. (1).

Table 1 Data used and specification of thermal bands

Dataset	Year	Source	Wavelength of thermal bands	
			Band number	Wavelength (λ) (in μm)
LANDSAT TM	1992	Earthexplorer.usgs.gov	6	11.45
LANDSAT TM	2005	Earthexplorer.usgs.gov	10	10.8
LANDSAT OLI AND TIRS	2016	Earthexplorer.usgs.gov	11	12.0

Source https://landsat.usgs.gov/what-are-band-designations-landsat-satellites

$$\mathrm{TB} = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)} \quad (1)$$

where, TB = effective at- satellite brightness temperature in Kelvin L_λ = Spectral radiance.k_1 and k_2 = constants present in the metadata of the image.

The resultant temperature was converted to degree Celsius. For better accuracy, emissivity values of different LULC were also incorporated to generate an emissivity map (Table 2). The calculated at-satellite brightness temperature is converted to land surface temperature with the help of the following formula (Eq. 2).

$$T = \mathrm{TB}/[1 + (\lambda \times \mathrm{TB}/c_2) \times \ln(e)] \quad (2)$$

where, λ = wavelength of emitted radiance $c_2 = h \times c/s = 1.4388 \times 10^{-2}$ mK = 14,388 μmKc = velocity of light = 2.998 × 108 m/sh = Planck's constant = 6.626×10^{-34} Jss = Boltzmann constant = 1.38×10^{-28} J/K

The values of λ are listed in the Table 1. LANDSAT TM and ETM$^+$ thermal infrared (TIR) data (Table 2) were utilized for local-scale studies of UHI [36]. Surface urban cool island intensity (UCII) and urban heat island intensity (UHII) were estimated considering the difference between the surface temperature of an urban area than that of its rural surroundings (Eq. 3) [37].

$$\Delta\mathrm{LST} = \mathrm{LST}_\mathrm{u} - \mathrm{LST}_\mathrm{r} \quad (3)$$

where, LST_u = mean LST of urban areaLST_r = mean LST of rural buffer area.

Table 2 Emissivity values of different land cover types

Land cover type	Emissivity
Built-up land	0.96
Vegetation cover	0.985
Water body	0.99
Bare rock/rock outcrop	0.94
Others	0.97

Later, the magnitude of both Surface Urban Heat Island (SUCI) and Surface Urban Cool Island (SUHI) were using the Eqs. (4) and (5) [38]:

$$\mathrm{SUHI} = T_\mathrm{u} - T_\mathrm{r} \quad (4)$$

$$\mathrm{SUCI} = T_\mathrm{r} - T_\mathrm{u} \quad (5)$$

where, T_u = mean LST of Urban or Core,T_r = mean LST of peri-urban/neighboring rural region

Land surface temperature of various UES was evaluated and analyzed to deduce the implications of UES dynamics over thermal comfort zones

Urban wetlands were demarcated using visual interpretation techniques for the years 1992, 2005 and 2016, and evaluated the changes inside and outside the municipal boundary over the periods. Later, the daily data MODIS data (MOD11A2) were analyzed to deduce the daily minimum, maximum, mean land surface temperature of the Bhubaneswar city for the period 2000-2017 in google earth engine.

3 Results and discussion

3.1 Demarcation of Urban ecosystem services

The spatio-temporal analysis of UES patches exhibited that the green patch decreased from 139.51 to 102.03 km^2 during 1992–2005 (26.86% decrease; Fig. 3 and Table 3). The decrease was primarily observed in the western, north-eastern, and southern parts of Bhubaneswar city. It further decreased to 70.16 km^2 in 2016 (49.70% decrease), which was observed along the centrally scattered green patches and along the northern parts. The blue patch depicted an episodic trend with decrease from 5.58 to 4.14 km^2 during 1992–2005 and later increased to 5.37 km^2 in 2016. The grey patch showed a major increase from 36.61 to 42.88 km^2 in 1992–2005 (17.13% growth), which was primarily evident in the southern and northern parts. The grey patch further increased to 105.42 km^2 (187.95% growth since 1992) in 2016 mainly depicting growth in the south-eastern and northern parts of Bhubaneswar city. The spatio-temporal analysis of the UES supply and demand patches of Bhubaneswar city for the years 1992, 2005 and

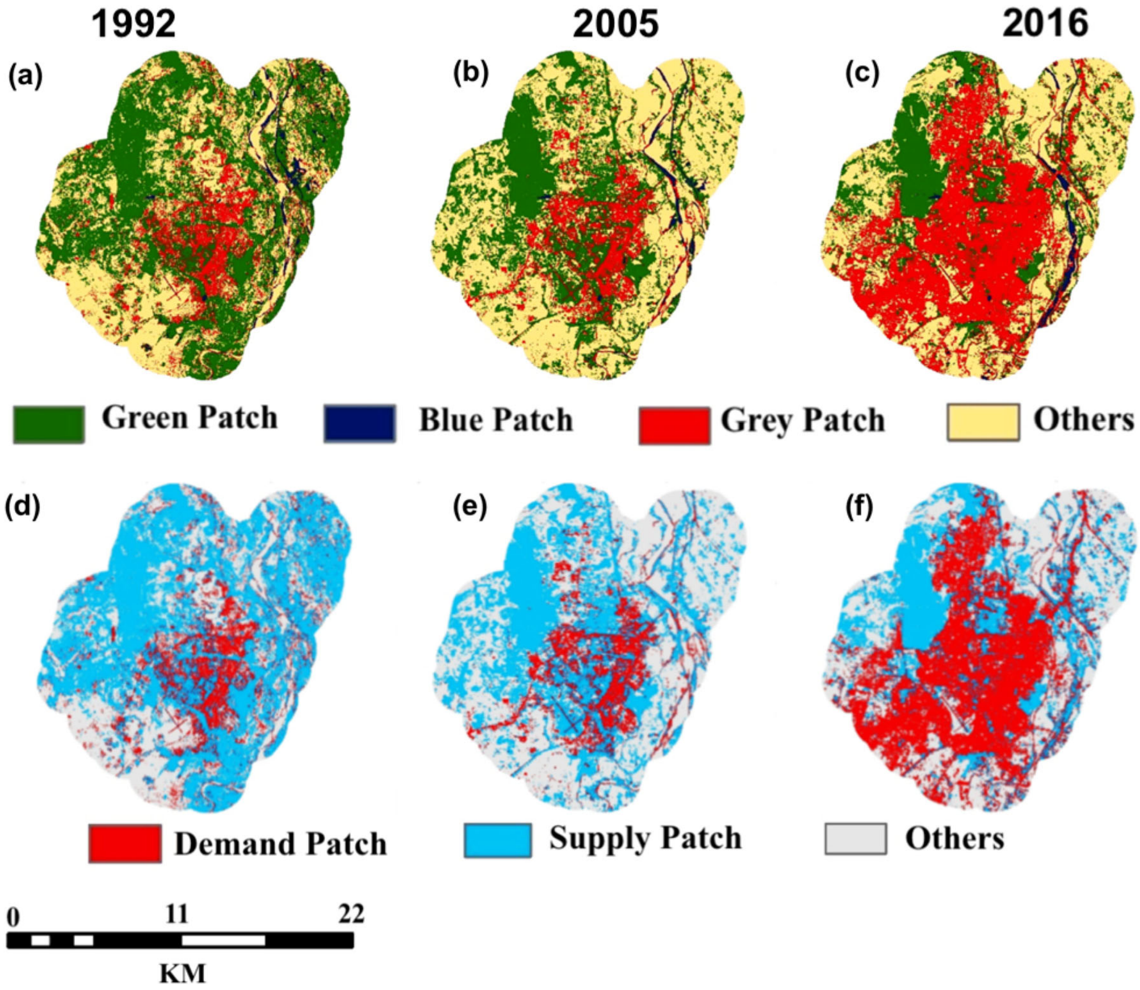

Fig. 3 Spatial distribution of **a–c** green, blue and grey patches, and **d–f** urban ecosystem services demand–supply patches in Bhubaneswar city during 1992–2016. (Color figure online)

Table 3 Area statistics of UES supply and demand patches in Bhubaneswar city during 1992–2016

UES patch		Area (km^2)			Change rate (percentage)		
		1992	2005	2016	1992–2005	2005–2016	1992–2016
Green & Blue patch	Supply	145.09	106.17	75.53	− 26.82	− 28.86	− 47.94
Grey patch	Demand	36.61	42.88	105.42	17.13	145.85	187.95
Others	Others	101.26	133.91	102.01	32.24	− 23.82	0.74

2016 suggested significant decrease in supply patches (blue–green patches) from 145.09 to 106.17 km^2 in 1992–2005 (26.82% decrease) (Fig. 3, Table 3). It further got reduced to 75.53 km^2 in 2016 (47.94% decrease since 1992). In contrast, the UES demand patches (grey patches) witnessed an increase from 36.61 to 42.88 km^2 during 1992–2005 (17.13% growth), and further to 105.42 km^2 in 2016 (187.95% growth since 1992).

3.2 Land surface temperature

The spatio-temporal assessment of the LST exhibited an increase in the spatial extent of the thermally uncomfortable zone, whereas the area under the thermally comfortable zone experienced decrease from 1992 to 2016 (Fig. 4, Table 4). LST zones ranging between 19 and 26 °C is the most thermally comfortable region for mankind and considered as the most suitable. With the increase in the LST > 26 °C and decrease in LST < 19 °C, the dependency of artificial cooling/warming has been increased to

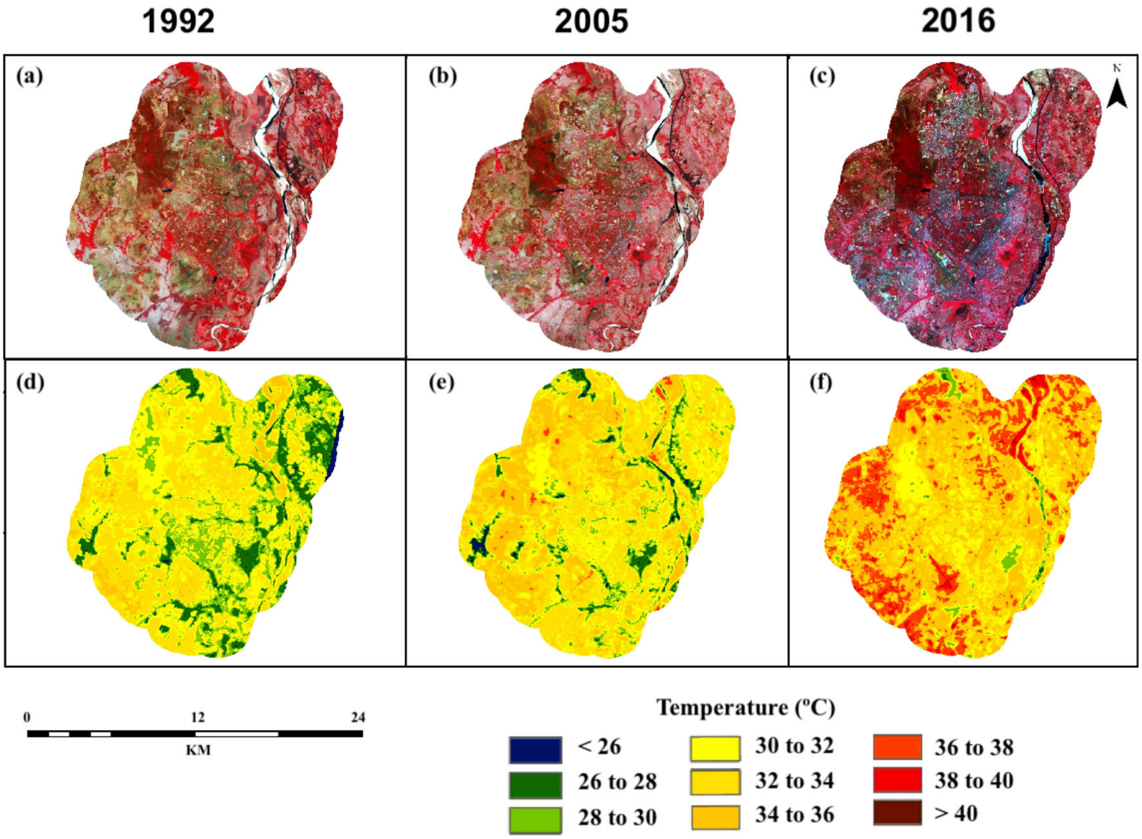

Fig. 4 Map representing satellite images of **a** 1992, **b** 2005 **c** 2016, and **d–f** spatio-temporal variations in land surface temperature in Bhubaneswar city during the respective years

Table 4 Area statistics of land surface temperatures in Bhubaneswar city during 1992–2016

Temperature range (°C)	Temperature intensity	Thermal comfort for humans	Area (km^2)		
			1992	2005	2016
< 26	Very Low	Comfortable	0.456	1.771	0
26–32	Low	Moderately uncomfortable	172.344	99.361	40.855
32–36	Moderate	Highly uncomfortable	108.491	179.792	185.163
36–40	High	Very highly uncomfortable	0.005	2.030	56.680
> 40	Very high	Extremely uncomfortable	0	0	0.257

maintain the liveable thermal environment. Therefore, the LST range between 26 and 32 °C was considered as moderately uncomfortable, LST 32 °C and 36 °C as highly uncomfortable, LST 36 °C and 40 °C as very highly uncomfortable and LST $\geq$ 40 °C as extremely uncomfortable. The study exhibited that the area under thermally comfortable zones (< 26 °C) increased from 0.45 to 1.771 km^2 during 1992–2005, but reduced to nil during 2005–2016 (Table 5). Similarly, the area under moderately uncomfortable thermal zones (26–32 °C) reduced from 172.34 to 99.361 km^2 during 1992–2005, and again decreased to 40.855 km^2 in 2016. In contrast, the area under the highly uncomfortable thermal zones (32–36 °C) increased from 108.491 to 179.79 km^2 during 1992–2005 and to 185.163 km^2 in 2016. Also, the area under very highly uncomfortable thermal zones (36–40 °C) increased from 0.005 to 2.03 km^2 during 1992–2005, and to 56.68 km^2 in 2016. The area under extremely uncomfortable thermal zones (> 40 °C) depicted nil values for the years 1992 and 2005 but got increased to 0.25 km^2 in the year 2016. The highly thermally uncomfortable zones (> 36 °C) were primarily associated with built-up and river

Table 5 UHI statistics of Bhubaneswar city during 1992–2016

Year	Mean surface temperature (°C)			
	Urban (BMC) A	Peri-Urban/Rural B	Study area (BMC + peri urban) C	SUHI D = A − B
1992	31.19	27.31	29.31	3.88
2005	32.46	32.34	32.39	0.12
2016	34.69	33.98	34.32	0.71
Periodic change (1992–2016)	3.5	6.67	5.01	− 3.17

sands, whereas areas with vegetation cover and higher moisture content land cover (water bodies and wetlands) depicted comparatively thermally comfortable zones (< 32 °C). The present study is focused on LST of the summer season, the values are primarily ranging from ∼ 22 to 43 °C and observed high increase in area under thermally extremely uncomfortable zones in Bhubaneswar city during 1992–2016, which has directly affected human health and living comfort. The spatio-temporal change may be attributed to the increase in the area under grey spaces during these periods, which induced high thermal inertia and surface temperature. The study indicates that the western region of the area has higher LST as compared to the eastern region, which may be attributed to the presence of Kuakhai river in the eastern side.

3.3 Urban heat island intensity

The investigation of spatial distribution of LST of Bhubaneswar city during 1992–2016 reveals that the mean LST of the entire study area was increased from 29.31 to 34.69 °C during 1992–2016 (Fig. 5, Tables 5 and 6). The mean LST of the urban area (within municipal boundary) was increased from 31.19 to 32.46 °C during 1992–2005 and further to 34.69 °C in 2016. whereas, the mean LST of the peri-urban area was significantly increased from 27.31 to 32.34 °C during 1992–2005 and to 33.98 °C in 2016. The study indicates that the mean LST of the peri-urban area increased more (6.67 °C) as compared to the urban extent (3.5 °C). The decrease in SUHI intensities from 3.88 to 0.17 °C during 1992–2016 exhibiting reduced impression of UHI in Bhubaneswar city due to high increase in LST in peri-urban region. This can be attributed to the significant decrease in blue and green patches in the peri-urban and rural area. Also, the increase in grey patches areas in the peri-urban region due to recent urban development's activities during 2005–16 lead to change in thermal environment of the region as these grey patches have lower albedo as compared to neighboring surfaces and hence depicts a much higher temperature.

3.4 Urban wetland monitoring

The study related to monitoring of urban wetland indicated continuous and significant decrease in wetland in the entire study area from 31.25 to 17.30 km^2 during 1992–2005 and later it again decreased to 13.38 km^2 in the year 2016 (57.18%: 1992–2016). The loss of wetland in urban areas (19.68 to 11.71 km^2) was observed higher as compared to the peri urban areas (11.57 to 5.41 km^2) during 1992–2016 (Fig. 6; Table 7). Such loss of wetlands in the urban and peri urban regions reflects the conspicuous impacts of anthropogenic activities in the regions, which may contribute to the increasing land surface temperature. Ecosystem is a set of interacting species with their local, non-biological environment functioning together to sustain life [5], whereas cities encompasses single or are composed of several individual ecosystems within urban environment [6].

3.5 Correlation analysis

A strong positive correlation ($R^2 = 0.75$) was evident between LST and UES grey patches, which implies the intrinsic relationship of grey patches and land surface temperature (Fig. 7). On the contrary, a strong negative correlation ($R^2 = -0.99$) between LST and UES supply (blue-green) patches indicating loss of heat sink zones in the region. The study indicated that with the expansion in urban areas together with diminishing of the blue-green patches, the thermal living natural condition has deteriorated.

3.6 Time series analysis of LST

The MODIS based time series analysis was performed for the mean, maximum and minimum LST of the urban area

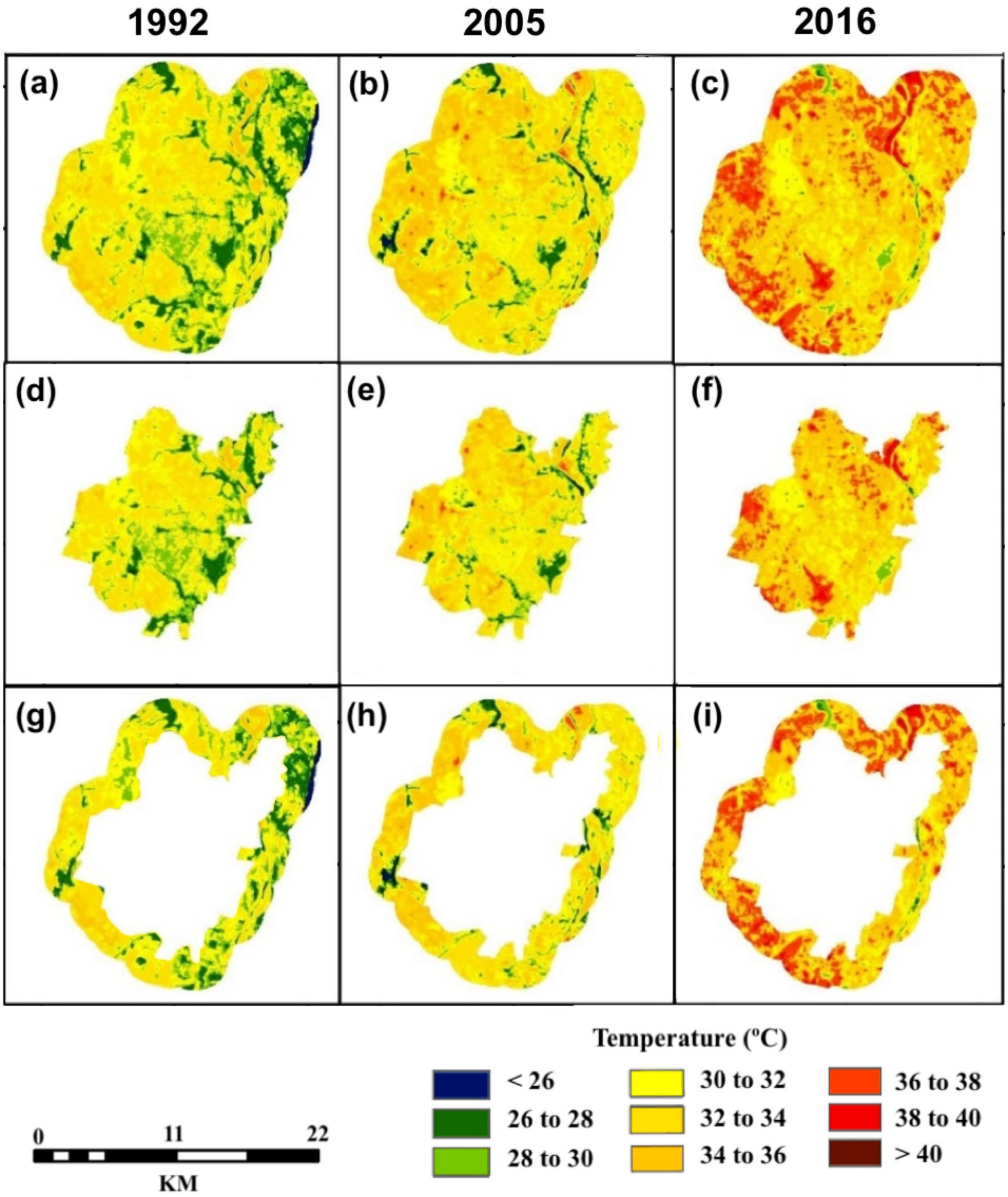

Fig. 5 UHI intensity map showing variations in LST in the **a–c** entire study area, **d–f** inside the Bhubaneswar municipal corporation (urban), and **g–i** peri-urban/rural areas during 1992–2016

for the period 2000–16. The study illustrates an insignificant decreasing trend of daily minimum, maximum and mean LST with episodic variations during 2000–17 (Supplementary material 1). The maximum LST exhibited reduction in very high LST in recent years as compared to previous years of observations, though the minimum LST range was further decreased with higher frequency in recent years of observations. The result exhibits that the mean LST was increased slightly from 30.55 to 30.76 °C recorded during 2000–2016. An overall fluctuating trend with the max LST value of 50.99 °C recorded in the year 2003, Whereas the minimum LST value of 6.49 °C was recorded in the year 2016. It exhibits that the mean LST has increased over the study period, indicating a decreased thermal comfort.

Table 6 Statistics of land surface temperature of Bhubaneswar city during 1992–2016 (units are in °C)

Year	Study area (Urban Peri-urban)				Urban (BMC)				Peri-urban/rural			
	Min	Max	Mean	Standard deviation	Min	Max	Mean	Standard deviation	Min	Max	Mean	Standard deviation
1992	25.26	36.37	29.31	2.29	25.26	36.37	31.19	1.95	25.26	35.93	27.31	2.33
2005	24.39	37.97	32.39	2.11	24.39	37.97	32.46	2.09	24.39	37.98	32.34	2.12
2016	26.91	41.43	34.32	2.02	27.06	41.43	34.69	1.88	26.91	40.87	33.98	2.1

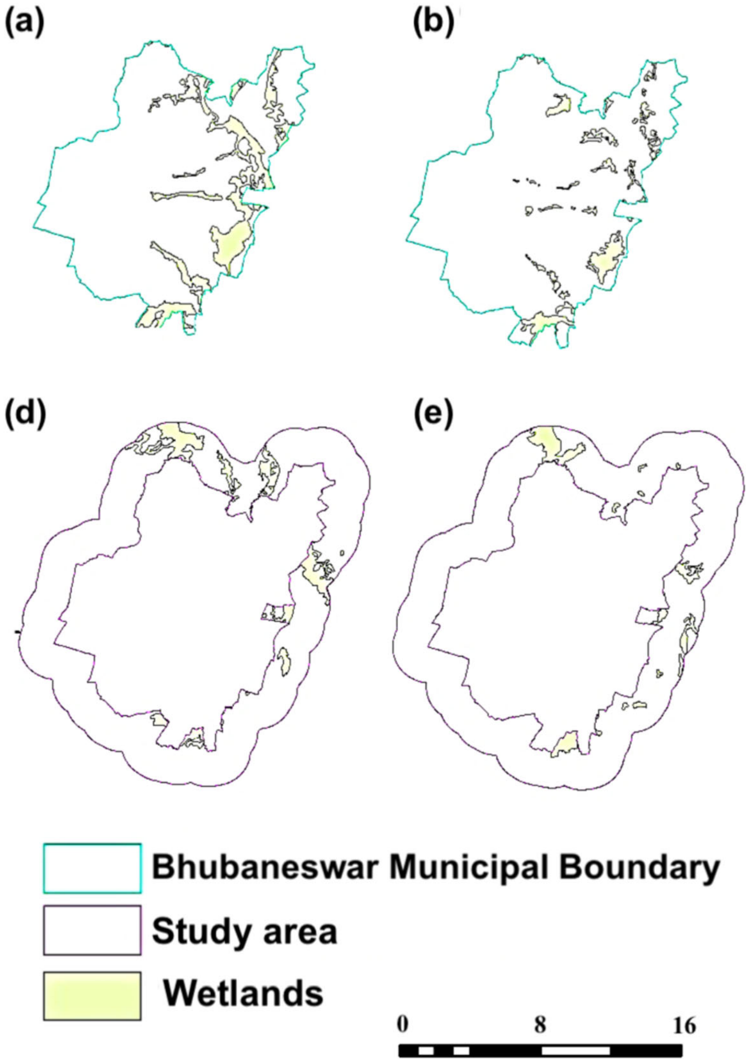

Fig. 6 Spatio-temporal distribution of wetlands in **a–c** Bhubaneswar municipal corporation (urban), and **d–f** peri-urban/rural aras during 2005–2016

3.7 Comparative assessment

The thermal comfort dynamics of Bhubaneswar city was compared with the other cities. Most of the studies exhibited a similar trend of decreasing thermal comfort with decrease in UES. In a recent study of the Barcelona Metropolitan Area by Lemus-Canovas et al. [39] depicted a decrease in thermal comfort, more prominently in spring and summer, with the increase in rate of urbanization. Another study by Parvez et al. [40] reported a steady rise in and surface temperature along with the changes in urban form and land use type, primarily in the industrial area compared to other urban forms, for over three decades in Jeddah [38]. Whereas, a study of Chandigarh by Sultana

Table 7 Area statistics of urban wetlands in urban and peri-urban regions of Bhubaneswar city

Year	Urban (km^2) A	Peri-urban/rural (km^2) B	Total (km^2) C = A + B	Total loss (%)
1992	19.68	11.57	31.25	–
2005	10.11	7.19	17.30	44.64
2016	7.97	5.41	13.38	22.65
Periodic change (1992–2016)	11.71	6.16	17.87	57.18

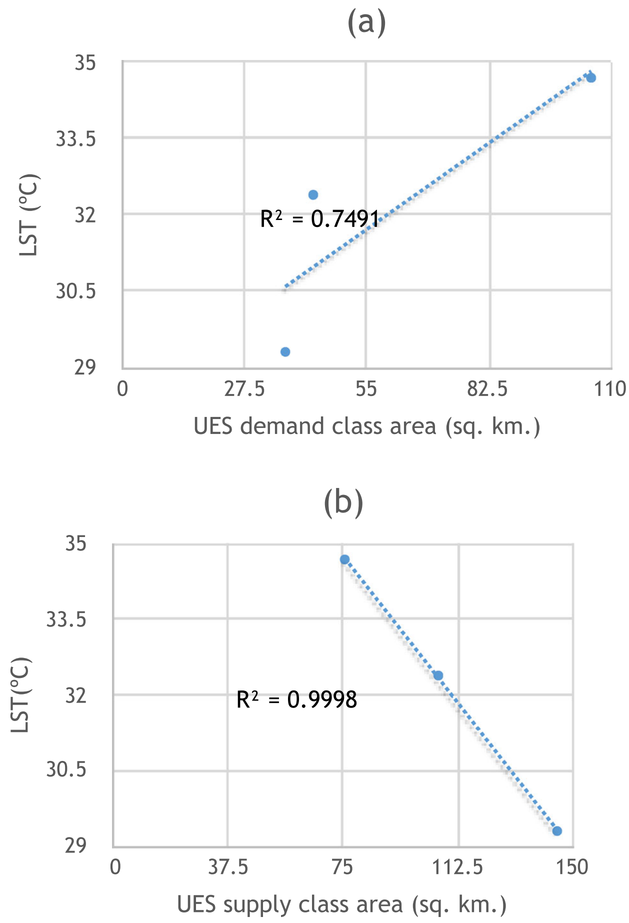

Fig. 7 Graph showing correlation between **a** LST and UES demand class area, and **b** LST and UES supply class area

and Satyanarayana [41] observed distinct Urban Heat Island (UHI) pockets over densely built-up areas, dry land, and industrial areas during both summer and winter seasons. Las Vegas has experienced a significant increase in LST on the temporal scale, accompanied by the considerable increase in area under high UHI with decrease in area under UHS. The increase in heat intensity transforms most of the urban heat sinks (UHS) into urban heat islands (UHI) [42]. These studies stressed to increase the quality of life in the summer season, naturally by managing the relationship between urban areas and green spaces considering the contribution of green cover in mitigating the air UHI and reducing the LST [38–40]. The role of green (vegetation) and blue (water body) UES has been described as essential factors in the mitigation of SUHI [42]. A negative correlation (> -0.8) between mean LST and Normalised Differential Vegetation Index (NDVI) was reported [41], all these results depict conformity to the present study with different intensities as the present study indicated a strong negative correlation of mean LST with blue-green patches ($R^2 = -0.99$).

It can be concluded that irrespective of its geographical location, the growing cities depict a similar trend of UHI and patterns of thermal comfort, which is based on its urban forms and its spatial arrangements (compactness). Along the temporal scale, LST has depicted an increase over the urban fabric, with different growth rates particularly in the industrial areas, dry lands and dense built-up. Whereas the green cover and water bodies contributed as major urban heat sink zones, though the LST in these zones has also been increasing over the years. The comparative study with other cities depicts a comparatively lower trend of increasing LST in the Bhubaneswar city due to comparatively less urban growth and its geographical location in the proximity of Bay of Bengal. These studies provide important inferences and insights necessary to mitigate and manage the increasing temperatures, to obtain higher comfort and hence better quality of life.

4 Conclusion

The study exhibits that UES consumers (i.e., grey patch) increased extensively from 36.61 to 105.4 km^2, (187.95%) during 1992–2016. On the contrary, the area of UES suppliers (*i.e.,* blue, and green patch) for the same period experienced a significant decline of 47.94%. The significant loss in ecosystem service providers indicates the increasing dependencies of urban milieu on its hinterlands. This also implies the deterioration of urban environment and ecosystem due to rapid increase of grey spaces by replacing blue-green UES leading to increase in thermally uncomfortable zones in the city and its vicinity. Although these grey spaces are the major centers of human settlements and varied urban functions, which contribute to the development of the city, the large continuum of grey spaces induce considerable disturbances in natural environment, biodiversity, etc. Satellite based land surface temperature analysis exhibits increase in thermally very highly uncomfortable (high LST: 35–40 °C) zones by 56.63 km^2 and decrease in area of thermally comfortable and moderately comfortable (moderate to low LST: 26–32 °C) zones by 131.48 km^2 (76.29% decrease). It was also observed that the urban, peri-urban, and neighboring rural areas witnessed an increase in temperature from thermally fairly-comfortable to highly uncomfortable ranges leading to unsuitable natural living conditions. Although, the LST was remained higher in urban areas as compared to its vicinity, the peri-urban and neighboring rural areas of Bhubaneswar city observed a high increase (by 24.42%) in mean LST (27.31–33.98 °C) as compared to the urban areas (31.19–34.69 °C by 11.22%) during 1992–2016 primarily due to high significant loss of green–blue spaces. This caused a conspicuous decrease in SUHI (from 3.88 to 0.71 °C) indicating an increase in thermally uncomfortable habitable conditions with the expansion of grey spaces together with reduction in the blue-green spaces in the peri-urban regions than Bhubaneswar city. The intrinsic relation of UES with thermal comfort is being established through a strong positive correlation of mean LST with grey spaces ($R^2 = 0.75$) in contrast to a stronger negative correlation with blue-green spaces ($R^2 = -0.99$). The MODIS based time series analysis depicted similar trends, wherein the mean LST was slightly increased from 30.55 to 30.76 °C during 2000–16. Although the city has witnessed an increase in LST over the period, it is not as severe as other major growing cities due to comparatively lower rate of urban growth, juvenile stage of urban life cycle, intermittent blue-green spaces, and its geographical proximity to Bay of Bengal. The study suggests the adoption of suitable urban planning measures to protect existing and augment blue-green spaces in the urban and peri-urban regions to restore thermally suitable natural living conditions.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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