



## SoilTemp: A global database of near-surface temperature

Jonas Lembrechts, Juha Aalto, Michael Ashcroft, Pieter de Frenne, Martin Kopecký, Jonathan Roger Michel Henri Lenoir, Miska Luoto, Ilya Maclean, Olivier Roupsard, Eduardo Fuentes-lillo, et al.

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MR. JONAS J. LEMBRECHTS (Orcid ID : 0000-0002-1933-0750)

MR. JUHA AALTO (Orcid ID : 0000-0001-6819-4911)

DR. MICHAEL B ASHCROFT (Orcid ID : 0000-0003-2157-5965)

DR. PIETER DE FRENNE (Orcid ID : 0000-0002-8613-0943)

MR. MARTIN KOPECKÝ (Orcid ID : 0000-0002-1018-9316)

DR. ILYA M D MACLEAN (Orcid ID : 0000-0001-8030-9136)

DR. JUHA ALATALO (Orcid ID : 0000-0001-5084-850X)

DR. ROBERT G. BJÖRK (Orcid ID : 0000-0001-7346-666X)

DR. MARTIN SVATEK (Orcid ID : 0000-0003-2328-4627)

PROF. ALISTAIR JUMP (Orcid ID : 0000-0002-2167-6451)

DR. ELLEN DORREPAAL (Orcid ID : 0000-0002-0523-2471)

DR. MICHELE CARBOGNANI (Orcid ID : 0000-0001-7701-9859)

DR. KOENRAAD VAN MEERBEEK (Orcid ID : 0000-0002-9260-3815)

DR. JIRI DOLEZAL (Orcid ID : 0000-0002-5829-4051)

MS. JULIA KEMPPINEN (Orcid ID : 0000-0001-7521-7229)

MR. PEKKA NIITYNEN (Orcid ID : 0000-0002-7290-029X)

PROF. JUERGEN KREYLING (Orcid ID : 0000-0001-8489-7289)

MS. SANNE GOVAERT (Orcid ID : 0000-0002-8939-1305)

MS. ANDREA LAMPRECHT (Orcid ID : 0000-0002-8719-026X)

DR. SYLVIA HAIDER (Orcid ID : 0000-0002-2966-0534)

PROF. MARTIN WILMKING (Orcid ID : 0000-0003-4964-2402)

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DR. JAN ALTMAN (Orcid ID : 0000-0003-4879-5773)

MR. MARTIN MACEK (Orcid ID : 0000-0002-5609-5921)

DR. MARIJN BAUTERS (Orcid ID : 0000-0003-0978-6639)

DR. MIGUEL PORTILLO-ESTRADA (Orcid ID : 0000-0002-0348-7446)

DR. ISLA H MYERS-SMITH (Orcid ID : 0000-0002-8417-6112)

DR. JÖRG G. STEPHAN (Orcid ID : 0000-0001-6195-7867)

MR. PATRICE DESCOMBES (Orcid ID : 0000-0002-3760-9907)

MR. CHRISTOPHER ANDREWS (Orcid ID : 0000-0003-2428-272X)

DR. REBECCA ANNE SENIOR (Orcid ID : 0000-0002-8208-736X)

DR. FATIH FAZLIOGLU (Orcid ID : 0000-0002-4723-3640)

DR. FERNANDO MOYANO (Orcid ID : 0000-0002-4090-5838)

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## SoilTemp: a global database of near-surface temperature

*Running title – SoilTemp: call for data*

**Jonas J. Lembrechts<sup>1</sup>, Juha Aalto<sup>2,3</sup>, Michael B. Ashcroft<sup>4,5</sup>, Pieter De Frenne<sup>6</sup>, Martin Kopecký<sup>7,8</sup>,  
Jonathan Lenoir<sup>9</sup>, Miska Luoto<sup>3</sup>, Ilya M. D. Maclean<sup>10</sup>, Olivier Roupsard<sup>11,12</sup>, Eduardo Fuentes-Lillo<sup>13,14,15,1</sup>,  
Rafael A. García<sup>13,14</sup>, Loïc Pellissier<sup>16,17</sup>, Camille Pitteloud<sup>16,17</sup>, Juha M. Alatalo<sup>18,19</sup>, Stuart W. Smith<sup>20,21</sup>,  
Robert G. Björk<sup>22,23</sup>, Lena Muffler<sup>24,25</sup>, Simone Cesarz<sup>26,27</sup>, Felix Gottschall<sup>26,27</sup>, Amanda Ratier Backes<sup>28,26</sup>,  
Joseph Okello<sup>29,30</sup>, Josef Urban<sup>31,32</sup>, Roman Plichta<sup>31</sup>, Martin Svátek<sup>31</sup>, Shyam S. Phartyal<sup>33,34</sup>, Sonja**

Wipf<sup>35,36</sup>, Nico Eisenhauer<sup>26,27</sup>, Mihai Pușcaș<sup>37</sup>, Pavel Dan Turtureanu<sup>38</sup>, Andrej Varlagin<sup>39</sup>, Romina D. Dimarco<sup>40</sup>, Alistair S. Jump<sup>41</sup>, Krystal Randall<sup>42</sup>, Ellen Dorrepaal<sup>43</sup>, Keith Larson<sup>43</sup>, Josefine Walz<sup>43</sup>, Luca Vitale<sup>44</sup>, Miroslav Svoboda<sup>8</sup>, Rebecca Finger Higgins<sup>45</sup>, Aud H. Halbritter<sup>46</sup>, Salvatore R. Curasi<sup>47</sup>, Ian Klupar<sup>47</sup>, Austin Koontz<sup>48</sup>, William D. Pearse<sup>48,49</sup>, Elizabeth Simpson<sup>48</sup>, Michael Stemkovski<sup>48</sup>, Bente Jessen Graae<sup>20</sup>, Mia Vedel Sørensen<sup>20</sup>, Toke T. Høye<sup>50</sup>, M. Rosa Fernández Calzado<sup>51</sup>, Juan Lorite<sup>51</sup>, Michele Carbognani<sup>52</sup>, Marcello Tomaselli<sup>52</sup>, T'ai G. W. Forte<sup>52</sup>, Alessandro Petraglia<sup>52</sup>, Stef Haesen<sup>53</sup>, Ben Somers<sup>53</sup>, Koenraad Van Meerbeek<sup>53</sup>, Mats P. Björkman<sup>22,23</sup>, Kristoffer Hylander<sup>54</sup>, Sonia Merinero<sup>55</sup>, Mana Gharun<sup>56</sup>, Nina Buchmann<sup>56</sup>, Jiri Dolezal<sup>7,57</sup>, Radim Matula<sup>8</sup>, Andrew D. Thomas<sup>58</sup>, Joseph J. Bailey<sup>59</sup>, Dany Ghosn<sup>60</sup>, George Kazakis<sup>60</sup>, Miguel Angel de Pablo<sup>61</sup>, Julia Kemppinen<sup>3</sup>, Pekka Niittynen<sup>3</sup>, Lisa Rew<sup>62</sup>, Tim Seipel<sup>62</sup>, Christian Larson<sup>62</sup>, James D. M. Speed<sup>63</sup>, Jonas Ardö<sup>64</sup>, Nicoletta Cannone<sup>65</sup>, Mauro Guglielmin<sup>66</sup>, Francesco Malfasi<sup>66</sup>, Maaike Y. Bader<sup>67</sup>, Rafaella Canessa<sup>67</sup>, Angela Stanisci<sup>68</sup>, Juergen Kreyling<sup>24</sup>, Jonas Schmeddes<sup>24</sup>, Laurenz Teuber<sup>24</sup>, Valeria Aschero<sup>69,70</sup>, Marek Čiliak<sup>71</sup>, František Máliš<sup>72</sup>, Pallieter De Smedt<sup>6</sup>, Sanne Govaert<sup>6</sup>, Camille Meeussen<sup>6</sup>, Pieter Vangansbeke<sup>6</sup>, Khatuna Gigauri<sup>73</sup>, Andrea Lamprecht<sup>74</sup>, Harald Pauli<sup>74</sup>, Klaus Steinbauer<sup>74</sup>, Manuela Winkler<sup>74</sup>, Masahito Ueyama<sup>75</sup>, Martin A. Nuñez<sup>76</sup>, Tudor-Mihai Ursu<sup>77</sup>, Sylvia Haider<sup>28,26</sup>, Ronja E. M. Wedegärtner<sup>20</sup>, Marko Smiljanic<sup>78</sup>, Mario Trouillier<sup>78</sup>, Martin Wilmking<sup>78</sup>, Jan Altman<sup>7</sup>, Josef Brůna<sup>7</sup>, Lucia Hederová<sup>7</sup>, Martin Macek<sup>7</sup>, Matěj Man<sup>7</sup>, Jan Wild<sup>7</sup>, Pascal Vittoz<sup>79</sup>, Meelis Pärtel<sup>80</sup>, Peter Barančok<sup>81</sup>, Róbert Kanka<sup>81</sup>, Jozef Kollár<sup>81</sup>, Andrej Palaj<sup>81</sup>, Agustina Barros<sup>70</sup>, Ana Clara Mazzolari<sup>70</sup>, Marijn Bauters<sup>29</sup>, Pascal Boeckx<sup>29</sup>, José Luis Benito Alonso<sup>82</sup>, Shengwei Zong<sup>83</sup>, Valter Di Cecco<sup>84</sup>, Zuzana Sitková<sup>85</sup>, Katja Tielbörger<sup>86</sup>, Liesbeth van den Brink<sup>86</sup>, Robert Weigel<sup>25</sup>, Jürgen Homeier<sup>25</sup>, C. Johan Dahlberg<sup>54,87</sup>, Sergiy Medinets<sup>88</sup>, Volodymyr Medinets<sup>88</sup>, Hans J. De Boeck<sup>1</sup>, Miguel Portillo-Estrada<sup>1</sup>, Lore T. Verryckt<sup>1</sup>, Ann Milbau<sup>89</sup>, Gergana N. Daskalova<sup>90</sup>, Haydn J. D. Thomas<sup>90</sup>, Isla H. Myers-Smith<sup>90</sup>, Benjamin Blonder<sup>91,92</sup>, Jörg G. Stephan<sup>93</sup>, Patrice Descombes<sup>16,17,94</sup>, Florian Zellweger<sup>94</sup>, Esther R. Frei<sup>35,94</sup>, Bernard Heinesch<sup>95</sup>, Christopher Andrews<sup>96</sup>, Jan Dick<sup>96</sup>, Lukas Siebicke<sup>97</sup>, Adrian Rocha<sup>98</sup>, Rebecca A. Senior<sup>99</sup>, Christian Rixen<sup>35</sup>, Juan J. Jimenez<sup>100</sup>, Julia Boike<sup>101,102</sup>, Aníbal Pauchard<sup>13,14</sup>, Thomas Scholten<sup>103</sup>, Brett Scheffers<sup>104</sup>, David Klinges<sup>105</sup>, Edmund W. Basham<sup>105</sup>, Jian Zhang<sup>106</sup>, Zhaochen Zhang<sup>106</sup>, Charly Géron<sup>107</sup>, Fatih Fazlioglu<sup>108</sup>, Onur Candan<sup>108</sup>, Jhonatan Sallo Bravo<sup>109</sup>, Filip Hrbacek<sup>110</sup>, Kamil Laska<sup>110</sup>, Edoardo Cremonese<sup>111</sup>, Peter Haase<sup>112,113</sup>, Fernando E. Moyano<sup>97</sup>, Christian Rossi<sup>114,115,36</sup>, Ivan Nijs<sup>1</sup>

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\*Corresponding author, OrcID = <https://orcid.org/0000-0002-1933-0750>,  
[Jonas.lembrechts@uantwerpen.be](mailto:Jonas.lembrechts@uantwerpen.be), +3232651727

### **OrcIDs (alphabetically ordered)**

Juha Aalto <https://orcid.org/0000-0001-6819-4911>  
Juha M. Alatalo <https://orcid.org/0000-0001-5084-850X>  
Jan Altman <https://orcid.org/0000-0003-4879-5773>  
Jonas Ardö <https://orcid.org/0000-0002-9318-0973>  
Valeria Aschero <https://orcid.org/0000-0003-3865-4133>  
Maaike Y Bader <http://orcid.org/0000-0003-4300-7598>  
Peter Barančok <https://orcid.org/0000-0003-1171-2524>  
Edmund Basham <https://orcid.org/0000-0002-0167-7908>  
José-Luis Benito-Alonso <https://orcid.org/0000-0003-1086-8834>  
Robert G. Björk <https://orcid.org/0000-0001-7346-666X>  
Mats P. Björkman <https://orcid.org/0000-0001-5768-1976>  
Julia Boike <https://orcid.org/0000-0002-5875-2112>  
Josef Brůna <https://orcid.org/0000-0002-4839-4593>  
Nina Buchmann <https://orcid.org/0000-0003-0826-2980>  
Onur Candan <https://orcid.org/0000-0002-9254-4122>  
Rafaella Canessa <https://orcid.org/0000-0002-6979-9880>  
Michele Carbognani <https://orcid.org/0000-0001-7701-9859>  
Marek Čiliak <https://orcid.org/0000-0002-6720-9365>  
Edoardo Cremonese <https://orcid.org/0000-0002-6708-8532>  
Salvatore R. Curasi: <https://orcid.org/0000-0002-4534-3344>  
C. Johan Dahlberg <https://orcid.org/0000-0003-0271-3306>  
Gergana Daskalova <https://orcid.org/0000-0002-5674-5322>  
Miguel Ángel de Pablo Hernández <https://orcid.org/0000-0002-4496-2741>  
Pallietter De Smedt <https://orcid.org/0000-0002-3073-6751>  
Jiri Dolezal <https://orcid.org/0000-0002-5829-4051>  
Nico Eisenhower <https://orcid.org/0000-0002-0371-6720>  
Fatih Fazlioglu <https://orcid.org/0000-0002-4723-3640>  
T'ai G. W. Forte <https://orcid.org/0000-0002-8685-5872>  
Esther R. Frei <https://orcid.org/0000-0003-1910-7900>  
Charly Geron: <https://orcid.org/0000-0001-7912-4708>  
Mana Gharun <https://orcid.org/0000-0003-0337-7367>  
Dany Ghosn <https://orcid.org/0000-0003-1898-9681>  
Felix Gottschall <https://orcid.org/0000-0002-1247-8728>  
Sanne Govaert <https://orcid.org/0000-0002-8939-1305>  
Peter Haase <https://orcid.org/0000-0002-9340-0438>

Stef Haesen <https://orcid.org/0000-0002-4491-4213>  
Sylvia Haider <https://orcid.org/0000-0002-2966-0534>  
Bernard Heinesch <https://orcid.org/0000-0001-7594-6341>  
Toke T. Høye <https://orcid.org/0000-0001-5387-3284>  
Filip Hrbacek <https://orcid.org/0000-0001-5032-9216>  
Juan J. Jiménez <https://orcid.org/0000-0003-2398-0796>  
Alistair S. Jump <https://orcid.org/0000-0002-2167-6451>  
Róbert Kanka <https://orcid.org/0000-0002-7071-7280>  
Julia Kempainen <https://orcid.org/0000-0001-7521-7229>  
Austin Koontz <https://orcid.org/0000-0002-6103-5894>  
Andrea Lamprecht <https://orcid.org/0000-0002-8719-026X>  
Christian Larson <https://orcid.org/0000-0002-7567-4953>  
Kamil Laska <https://orcid.org/0000-0002-5199-9737>  
Jonathan Lenoir <http://orcid.org/0000-0003-0638-9582>  
Juan Lorite <https://orcid.org/0000-0003-4617-8069>  
František Máliš <https://orcid.org/0000-0003-2760-6988>  
Matěj Man <https://orcid.org/0000-0002-4557-8768>  
Sergiy Medinets <http://orcid.org/0000-0001-5980-1054>  
Volodymyr Medinets <https://orcid.org/0000-0001-7543-7504>  
Camille Meeussen <https://orcid.org/0000-0002-5869-4936>  
Ann Milbau <https://orcid.org/0000-0003-3555-8883>  
Fernando E. Moyano <https://orcid.org/0000-0002-4090-5838>  
Lena Muffler <https://orcid.org/0000-0001-8227-7297>  
Isla Myers-Smith <https://orcid.org/0000-0002-8417-6112>  
Pekka Niittynen <https://orcid.org/0000-0002-7290-029X>  
Ivan Nijs <https://orcid.org/0000-0003-3111-680X>  
Andrej Palaj <https://orcid.org/0000-0001-7054-4183>  
Harald Pauli <https://orcid.org/0000-0002-9842-9934>  
William D. Pearse <https://orcid.org/0000-0002-6241-3164>  
Shyam S. Phartyal <https://orcid.org/0000-0003-3266-6619>  
Mihai Puşcaş <https://orcid.org/0000-0002-2632-640X>  
Krystal Randall <https://orcid.org/0000-0003-2507-1000>  
Lisa Rew <https://orcid.org/0000-0002-2818-3991>  
Christian Rossi <https://orcid.org/0000-0001-9983-8898>  
Olivier Rounsard <http://orcid.org/0000-0002-1319-142X>  
Jhonatan Sallo-Bravo <https://orcid.org/0000-0001-9007-4959>  
Brett Scheffers <https://orcid.org/0000-0003-2423-3821>  
Thomas Scholten <https://orcid.org/0000-0002-4875-2602>  
Rebecca A. Senior <https://orcid.org/0000-0002-8208-736X>  
Zuzana Sitková <https://orcid.org/0000-0001-6354-6105>  
Stuart W. Smith <https://orcid.org/0000-0001-9396-6610>  
Ben Somers <https://orcid.org/0000-0002-7875-107X>  
James D. M. Speed <http://orcid.org/0000-0002-0633-5595>  
Klaus Steinbauer <https://orcid.org/0000-0002-3730-9920>  
Jörg G. Stephan <http://orcid.org/0000-0001-6195-7867>

*Martin Svátek* <https://orcid.org/0000-0003-2328-4627>  
*Miroslav Svoboda* <https://orcid.org/0000-0003-4050-3422>  
*Andrew Thomas* <https://orcid.org/0000-0002-1360-1687>  
*Haydn Thomas* <https://orcid.org/0000-0001-9099-6304>  
*Marcello Tomaselli* <https://orcid.org/0000-0003-4208-3433>  
*Pavel Dan Turtureanu* <https://orcid.org/0000-0002-7422-3106>  
*Masahito Ueyama* <https://orcid.org/0000-0002-4000-4888>  
*Josef Urban* <https://orcid.org/0000-0003-1730-947X>  
*Tudor-Mihai Ursu* <https://orcid.org/0000-0002-4898-6345>  
*Liesbeth van den Brink* <https://orcid.org/0000-0003-0313-8147>  
*Pieter Vangansbeke* <https://orcid.org/0000-0002-6356-2858>  
*Andrej Varlagin* <https://orcid.org/0000-0002-2549-5236>  
*Koenraad Van Meerbeek* <https://orcid.org/0000-0002-9260-3815>  
*Lore T. Verryckt* <https://orcid.org/0000-0002-9452-5216>  
*Pascal Vittoz* <https://orcid.org/0000-0003-4218-4517>  
*Josefine Walz* <https://orcid.org/0000-0002-0715-8738>  
*Ronja E. M. Wedegärtner* <https://orcid.org/0000-0003-4633-755X>  
*Robert Weigel* <https://orcid.org/0000-0001-9685-6783>  
*Jan Wild* <https://orcid.org/0000-0003-3007-4070>  
*Martin Wilmking* <https://orcid.org/0000-0003-4964-2402>  
*Manuela Winkler* <http://orcid.org/0000-0002-8655-9555>  
*Sonja Wipf* <http://orcid.org/0000-0002-3492-1399>  
*Florian Zellweger* <https://orcid.org/0000-0003-1265-9147>  
*Jian Zhang* <https://orcid.org/0000-0003-0589-6267>

<sup>1</sup> Research Group PLECO (Plants and Ecosystems), University of Antwerp, 2610 Wilrijk, Belgium, <sup>2</sup> Finnish Meteorological Inst., P.O. Box 503, FI-00101 Helsinki, Finland, <sup>3</sup> Dept of Geosciences and Geography, Gustaf Hållströmin katu 2a, FIN-00014 Univ. of Helsinki, Finland, <sup>4</sup> Centre for Sustainable Ecosystem Solutions, School of Biological Sciences, University of Wollongong, Wollongong, Australia, <sup>5</sup> Australian Museum, Sydney, Australia, <sup>6</sup> Forest & Nature Lab, Department of Environment, Ghent University, Geraardsbergsesteenweg 267, 9090 Melle-Gontrode, Belgium, <sup>7</sup> Institute of Botany of the Czech Academy of Sciences, Zámek 1, CZ-25243, Průhonice, Czech Republic, <sup>8</sup> Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Kamýcká 129, CZ-165 21, Prague 6 - Suchbát, Czech Republic, <sup>9</sup> UR 'Ecologie et Dynamique des Systèmes Anthropisés' (EDYSAN, UMR 7058 CNRS-UPJV), Univ. de Picardie Jules Verne, Amiens, France, <sup>10</sup> Environment and Sustainability Institute, University of Exeter, Penryn Campus, Penryn, UK, TR10 9FE, <sup>11</sup> CIRAD, UMR Eco&Sols, B.P. 1386, CP 18524, Dakar, Senegal, <sup>12</sup> Eco&Sols, Univ Montpellier, CIRAD, INRAE, IRD, Institut Agro, Montpellier, France, <sup>13</sup> Laboratorio de Invasiones Biológicas (LIB), Facultad de Ciencias Forestales, Universidad de Concepción, Concepción, Chile, <sup>14</sup> Instituto de Ecología y Biodiversidad (IEB), Santiago, Chile, <sup>15</sup> School of Education and Social Sciences, Adventist University of Chile, Chile, <sup>16</sup> Landscape Ecology, Institute of Terrestrial Ecosystems, Department of Environmental Systems Science, ETH Zürich, 8092 Zürich, Switzerland, <sup>17</sup> Unit of Land Change Science, Swiss Federal Research Institute WSL, 8903 Birmensdorf, Switzerland, <sup>18</sup> Department of Biological and Environmental Sciences, Qatar University, Doha, Qatar, <sup>19</sup> Environmental Science Center, Qatar University, Doha, Qatar, <sup>20</sup> Department of Biology, Norwegian University of Science and Technology, 7491 Trondheim, Norway, <sup>21</sup> Asian School of Environment, Nanyang Technological University, 42 Nanyang Ave, Singapore 639815, Singapore, <sup>22</sup> Department of Earth Sciences, University of Gothenburg, P.O. Box 460, SE-40530 Gothenburg, Sweden, <sup>23</sup> Gothenburg Global Biodiversity Centre, P.O. Box 461, SE-405 30 Gothenburg, Sweden, <sup>24</sup> Experimental Plant Ecology, Institute of Botany and Landscape Ecology, University of Greifswald, D-17487 Greifswald, Germany, <sup>25</sup> Plant Ecology, Albrecht-von-Haller-Institute for Plant Sciences, University of Goettingen, 37073 Goettingen, Germany, <sup>26</sup> German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Germany, <sup>27</sup> Institute of Biology, Leipzig University, Leipzig, Germany, <sup>28</sup> Institute of Biology / Geobotany and Botanical Garden, Martin Luther University Halle-Wittenberg, Halle (Saale), Germany, <sup>29</sup> Isotope Bioscience Laboratory - ISOFYS, Ghent University, Coupure Links 653, 9000 Gent, Belgium, <sup>30</sup> Mountains of the Moon University, P.O Box 837, Fort Portal, Uganda, <sup>31</sup> Department of Forest Botany, Dendrology and Geobiocoenology, Mendel University in Brno, Czech Republic, <sup>32</sup> Siberian Federal University, Krasnoyarsk, Russia, <sup>33</sup> School of Ecology and Environment Studies, Nalanda University, Rajgir, India, <sup>34</sup> Department of Forestry and NR, H.N.B. Garhwal University, Srinagar-Garhwal, India, <sup>35</sup> WSL Institute for Snow and Avalanche Research SLF, 7260 Davos, Switzerland, <sup>36</sup> Swiss National Park, Chastè Planta-Wildenberg, 7530 Zernez, Switzerland, <sup>37</sup> A. Borza Botanical Garden and Department of Taxonomy and Ecology, Faculty of Biology and Geology, Babeş-Bolyai University, Cluj-Napoca, Romania, <sup>38</sup> A. Borza Botanical Garden, Babeş-Bolyai University, Cluj-Napoca, Romania, <sup>39</sup> A.N. Severtsov Institute of Ecology and Evolution, Russian Academy of Sciences, 119071, Leninsky pr.33, Moscow, Russia, <sup>40</sup> Grupo de Ecología de Poblaciones de Insectos, IFAB (INTA - CONICET), Isla Victoria 4450, Bariloche, Argentina, <sup>41</sup> Biological and Environmental Sciences, Faculty of Natural Sciences, University of Stirling, Scotland, FK9 4LA, <sup>42</sup> Centre for Sustainable Ecosystem Solutions, School of Earth, Atmospheric and Life Sciences, University of Wollongong, Wollongong, New South Wales, 2522, Australia, <sup>43</sup> Climate Impacts Research Centre, Department of Ecology and Environmental Sciences, Umeå University, Abisko, Sweden, <sup>44</sup> CNR - Institute for mediterranean Agricultural and Forest Systems, Via Patacca 85, ercolano (napoli), Italy, <sup>45</sup> Dartmouth College, Hanover, NH, USA, <sup>46</sup> Department of Biological Sciences and Bjerknes Centre for Climate Research, University of Bergen, N-5020 Bergen, Norway, <sup>47</sup> Department of Biological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA, <sup>48</sup> Department of Biology and Ecology Center, Utah State University, 5305 Old Main Hill, Logan, UT 84322, USA, <sup>49</sup> Department of Life Sciences, Imperial College, Silwood Park Campus, Ascot, Berkshire SL5 7PY, UK, <sup>50</sup> Department of Bioscience and Arctic Research Centre, Grenåvej 14, 8410 Rønne, Denmark, <sup>51</sup> Department of Botany, University of Granada,



18071, Granada, Spain, <sup>52</sup> Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parco Area delle Scienze 11/A, 43124 Parma, Italy, <sup>53</sup> Department of Earth and Environmental Sciences, Celestijnenlaan 200E, 3001 Leuven, Belgium, <sup>54</sup> Department of Ecology, Environment and Plant Sciences and Bolin Centre for Climate Research, Stockholm University, 106 91 Stockholm, Sweden, <sup>55</sup> Department of Ecology, Environment and Plant Sciences, Stockholm University, SE-106 91 Stockholm, Sweden, <sup>56</sup> Department of Environmental Systems Science, ETH Zurich, Universitaetstrasse 2, 8092 Zurich, Switzerland, <sup>57</sup> Faculty of Science, Department of Botany, University of South Bohemia, Na Zlaté Stoce 1, 37005 České Budějovice, Czech Republic, <sup>58</sup> Department of Geography and Earth Sciences, Aberystwyth University, Wales, UK, <sup>59</sup> Department of Geography, York St John University, Lord Mayor's Walk, York, YO31 7EX, United Kingdom, <sup>60</sup> Department of Geo-information in Environmental Management, Mediterranean Agronomic Institute of Chania, PO Box 85, 73100 Chania, Greece, <sup>61</sup> Department of Geology, Geography and Environment. University of Alcalá. 28805 Alcalá de Henares, Madrid, Spain., <sup>62</sup> Department of Land Resources and Environmental Sciences, Montana State University, Bozeman MT, USA, 59717, <sup>63</sup> Department of Natural History, NTNU University Museum, Norwegian University of Science and Technology, NO-7491 Trondheim Norway, <sup>64</sup> Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12 223 62 Lund Sweden, <sup>65</sup> Department of Science and High Technology, Insubria University, Via Valleggio 11, 22100 Como, Italy, <sup>66</sup> Department of Theoretical and Applied Sciences, Insubria University, Via Dunant 3, 21100 Varese, Italy, <sup>67</sup> Ecological Plant Geography, Faculty of Geography, University of Marburg, Deutschhausstr. 10, 35032, Marburg, Germany, <sup>68</sup> EnvixLab, Dipartimento di Bioscienze e Territorio, Università degli Studi del Molise, Via Duca degli Abruzzi s.n.c., 86039 Termoli, Italy, <sup>69</sup> Facultad de Ciencias Exactas y Naturales, Universidad Nacional de Cuyo, <sup>70</sup> Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA), CONICET, CCT-Mendoza, <sup>71</sup> Faculty of Ecology and Environmental Sciences, Technical University in Zvolen, T.G.Masaryka 24, 960 01 Zvolen, Slovakia, <sup>72</sup> Faculty of Forestry, Technical University in Zvolen, T.G.Masaryka 24, 960 01 Zvolen, Slovakia, <sup>73</sup> Georgian Institute of Public Affairs, Tbilisi, Georgia, <sup>74</sup> GLORIA Coordination, Institute for Interdisciplinary Mountain Research, Austrian Academy of Sciences (ÖAW) & Department of Integrative Biology and Biodiversity Research, University of Natural Resources and Life Sciences Vienna (BOKU), Silbergasse 30/3, 1190 Vienna, Austria, <sup>75</sup> Graduate School of Life and Environmental Sciences, Osaka Prefecture University, 599-8531, Japan, <sup>76</sup> Grupo de Ecología de Invasiones, INIBIOMA, CONICET/ Universidad Nacional del Comahue, Av. de los Pioneros 2350, Bariloche 8400, Argentina, <sup>77</sup> Institute of Biological Research Cluj-Napoca, National Institute of Research and Development for Biological Sciences, Bucharest, Romania, <sup>78</sup> Institute of Botany and Landscape Ecology, University Greifswald, D-17487 Greifswald, Germany, <sup>79</sup> Institute of Earth Surface Dynamics, Faculty of Geosciences and Environment, University of Lausanne, Géopolis, 1015 Lausanne, Switzerland, <sup>80</sup> Institute of Ecology and Earth Sciences, University of Tartu, Lai 40, Tartu 51005, Estonia, <sup>81</sup> Institute of Landscape Ecology Slovak Academy of Sciences, Štefánikova 3, 81499 Bratislava, Slovakia, <sup>82</sup> Jolube Consultor Botánico. C/Mariano R de Ledesma, 4. E-22700 Jaca, Huesca, SPAIN, <sup>83</sup> Key Laboratory of Geographical Processes and Ecological Security in Changbai Mountains, Ministry of Education, School of Geographical Sciences, Northeast Normal University, Changchun 130024, China, <sup>84</sup> Majella Seed Bank, Majella National Park, Colle Madonna, 66010 Lama dei Peligni, Italy, <sup>85</sup> National Forest Centre, Forest Research Institute Zvolen, T. G. Masaryka 22, 96001 Zvolen, Slovakia, <sup>86</sup> Plant Ecology Group, Department of Evolution and Ecology, University of Tübingen, Tübingen, Germany, <sup>87</sup> the County Administrative Board of Västra Götaland, SE-403 40 Gothenburg, Sweden, <sup>88</sup> Regional Centre for Integrated Environmental Monitoring, Odesa National I.I. Mechnikov University, 7 Mayakovskogo lane, 65082 Odesa, Ukraine, <sup>89</sup> Research Institute for Nature and Forest (INBO), Havenlaan 88, bus 73, 1000 Brussel, Belgium, <sup>90</sup> School of GeoSciences, University of Edinburgh, King's Buildings, Edinburgh, EH9 3FF, United Kingdom, <sup>91</sup> School of Life Sciences, Arizona State University, Tempe, AZ, USA, <sup>92</sup> Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA 94720 USA, <sup>93</sup> Swedish University of Agricultural Sciences, Swedish Species Information Centre, Almas allé 8 E, 75651 Uppsala, Sweden, <sup>94</sup> Swiss Federal Research Institute WSL, 8903 Birmensdorf,

Switzerland, <sup>95</sup> TERRA Teaching and Research Center, Faculty of Gembloux Agro-Bio Tech, University of Liege, Passage des déportés, 2, 5030 Gembloux, Belgium, <sup>96</sup> UK Centre for Ecology & Hydrology, Bush Estate, Penicuik, Midlothian, EH26 0QB, United Kingdom, <sup>97</sup> University of Goettingen, Bioclimatology, Büsgenweg 2, 37077 Göttingen, Germany., <sup>98</sup> University of Notre Dame, Department of Biological Sciences and the Environmental Change Initiative, <sup>99</sup> Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ 08540, USA, <sup>100</sup> ARAID Research and Development, Zaragoza, Spain, <sup>101</sup> Alfred Wegener Institute Helmholtz Center for Polar and Marine Research, Telegrafenberg A45, 14473 Potsdam, Germany, <sup>102</sup> Geography Department, Humboldt-Universität zu Berlin, Germany, <sup>103</sup> Chair of Soil Science and Geomorphology, Department of Geosciences, University of Tuebingen, 72070 Tuebingen, Germany, <sup>104</sup> Department of Wildlife Ecology and Conservation, University of Florida, Gainesville, FL 32611, USA, <sup>105</sup> School of Natural Resources and Environment, University of Florida, Gainesville, FL 32611, USA, <sup>106</sup> Zhejiang Tiantong Forest Ecosystem National Observation and Research Station, School of Ecological and Environmental Sciences, East China Normal University, Shanghai 200241, China, <sup>107</sup> Biodiversity and Landscape, TERRA research centre, Gembloux Agro-Bio Tech, University of Liège, Gembloux, 5032, Belgium ; Research Group PLECO (Plants and Ecosystems), University of Antwerp, 2610 Wilrijk, Belgium, <sup>108</sup> Faculty of Arts and Sciences, Department of Molecular Biology and Genetics, Ordu University, 52200, Ordu, Turkey, <sup>109</sup> Universidad Nacional de San Antonio Abad del Cusco, Cusco, Peru, <sup>110</sup> Department of Geography, Masaryk University, Brno, Czech Republic, <sup>111</sup> Climate Change Unit, Environmental Protection Agency of Aosta Valley, Sain Christophe, Aosta, Italy, <sup>112</sup> Senckenberg Research Institute and Natural History Museum Frankfurt, 63571 Gelnhausen, Germany, <sup>113</sup> Faculty of Biology, University of Duisburg-Essen, 45141 Essen, Germany, <sup>114</sup> Remote Sensing Laboratories, Dept. of Geography, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland, <sup>115</sup> Research Unit Community Ecology, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland

## 1    **Abstract**

2    Current analyses and predictions of spatially-explicit patterns and processes in ecology most often rely on  
3    climate data interpolated from standardized weather stations. This interpolated climate data represents  
4    long-term average thermal conditions at coarse spatial resolutions only. Hence, many climate-forcing  
5    factors that operate at fine spatiotemporal resolutions are overlooked. This is particularly important in  
6    relation to effects of observation height (e.g. vegetation, snow and soil characteristics) and in habitats  
7    varying in their exposure to radiation, moisture and wind (e.g. topography, radiative forcing, or cold-air  
8    pooling). Since organisms living close to the ground relate more strongly to these microclimatic conditions  
9    than to free-air temperatures, microclimatic ground and near-surface data are needed to provide realistic  
10    forecasts of the fate of such organisms under anthropogenic climate change, as well as of the functioning  
11    of the ecosystems they live in.

12    To fill this critical gap, we highlight a call for temperature time series submissions to SoilTemp, a  
13    geospatial database initiative compiling soil and near-surface temperature data from all over the world.  
14    Currently this database contains time series from 7538 temperature sensors from 51 countries across all  
15    key biomes. The database will pave the way towards an improved global understanding of microclimate  
16    and bridge the gap between the available climate data and the climate at fine spatiotemporal resolutions  
17    relevant to most organisms and ecosystem processes.

18    **Keywords:** microclimate, soil climate, climate change, topoclimate, database, temperature, species  
19    distributions, ecosystem processes

## 20 **Introduction**

21 Current ecological research increasingly deals with large-scale patterns and processes, with global  
22 databases of species distributions and traits becoming increasingly available (Bruehlheide *et al.*, 2018,  
23 Kissling *et al.*, 2018, Kattge *et al.*, 2019). Analyses of these patterns and processes – and their predictions  
24 under anthropogenic climate change – often rely on global climatic grids at coarse spatial resolutions  
25 interpolated from standardized weather stations that represent long-term average atmospheric  
26 conditions (Lembrechts *et al.*, 2018). Moreover, sensors in these weather stations are shielded from direct  
27 solar radiation and located at ~2 meters above a frequently mown lawn (free-air temperature or  
28 'macroclimate', Jarraud, 2008). These climatic grids thus ignore many climate-forcing processes that  
29 operate near the ground surface, at fine spatiotemporal resolutions, and in environments that vary in  
30 their exposure to winds, radiation and moisture ('microclimate', Daly, 2006, Bramer *et al.*, 2018, Körner &  
31 Hiltbrunner, 2018). Importantly, while these microclimatic processes often operate at fine spatiotemporal  
32 resolutions, they can affect ecological relations both at the local and the global scale (De Frenne *et al.*,  
33 2013, Ashcroft *et al.*, 2014, Lembrechts *et al.*, 2019). For example, they can potentially protect ground-  
34 dwelling biota against long-term climate variability, providing microrefugia for these species to survive in  
35 locations deemed unsuitable in models using climate data at coarse spatial resolutions, or buffer  
36 organisms against short-term extreme events (De Frenne *et al.*, 2013, Lenoir *et al.*, 2017, Bramer *et al.*,  
37 2018, Suggitt *et al.*, 2018). Microclimates can however also expose organisms to more extreme  
38 temperatures, in which case distribution models that ignore such microclimates may erroneously predict  
39 species survival instead of extinction (Pincebourde & Casas, 2019). In order to provide realistic forecasts  
40 of species distributions and performance, as well as of the functioning of the ecosystems they operate in,  
41 climate data that incorporates microclimatic processes, ideally measured *in-situ*, are thus urgently needed  
42 (Körner & Hiltbrunner, 2018).

## 43 **Horizontal and vertical features driving microclimate**

44 The offset between micro- and macroclimate is particularly pronounced around the soil surface, as  
45 temperatures measured at 2 m above the ground can differ substantially from those at ground level, or in  
46 the layers just above and below it (Geiger, 1950, Lembrechts *et al.*, 2019). This offset can result from both  
47 'horizontal' and 'vertical' features (Fig. 1), and can exceed several degrees centigrade in annual averages.  
48 For example, Kearney (2019) modelled coarse-scale soil temperatures at various depths considering the  
49 vertical features affecting the radiation balance. These vertical features include the effects of vegetation  
50 characteristics (e.g. structure and cover), snow cover and soil characteristics (e.g. moisture content,

geological types, texture and bulk density) (Li, 1926, Zhang *et al.*, 2008, Lembrechts *et al.*, 2019). The result of these vertical features is not only an instantaneous temperature offset between air and soil temperatures, but also a buffering effect, i.e. the temporal variability in temperature changes is lower in the soil than in the air (Geiger, 1950, Ashcroft & Gollan, 2013). Horizontal processes on the other hand relate more to the spatial resolution of the climatic data. They can be broken up into those that require only fine-resolution environmental information for specific sites (e.g. effects of slope and aspect on radiation balances; Bennie *et al.*, 2008), and those where temperatures are also affected by neighboring locations (e.g. topographic shading, cold-air drainage and atmospheric temperature inversions, which are landscape context dependent; Whiteman, 1982, Ashcroft & Gollan, 2012).

How horizontal and vertical features interact to define differences between soil and air temperature may differ with the biome, season and day time. For example, in grasslands during summer, incoming short-wave solar radiation is usually the dominant factor determining daytime soil surface temperatures, which in turn result in higher air temperatures through convective heating (Geiger, 1950). However, during winter, horizontal processes such as cold-air drainage and coastal buffering can have larger effects, especially on overnight air temperatures, when air temperatures may be driving soil temperatures rather than vice-versa (Vitasse *et al.*, 2017). In dense forests, the situation is even more complex: upper canopies block the bulk of short wave solar radiation, such that sub-canopy temperatures are determined by convective heat transfer between the air surrounding the canopy and direct conductance through physical contact of different parts of the canopy layer, in addition to the limited radiation that does permeate the canopy (Körner & Paulsen, 2004, Lenoir *et al.*, 2017, Zellweger *et al.*, 2019). As a result, horizontal processes such as passing fronts, and winds blowing in hotter or colder air from outside the forest, will in large part define the – dampened – temperature patterns under forest canopies (Ashcroft *et al.*, 2008).

#### ***The need for microclimate data across the field of ecology***

Many organisms living in the soil and close to the soil surface (e.g. soil micro-organisms like fungi, ground arthropods, herbs, mosses, tree seedlings and small vertebrates) only experience fine-scale soil and/or near-surface temperatures, and thus likely relate less strongly to free-air temperatures (Randin *et al.*, 2009, Niittynen & Luoto, 2017, Lembrechts *et al.*, 2019). This may be reflected in a species' distribution, but also their morphology, physiology and behavior (Körner & Paulsen, 2004, Kearney *et al.*, 2009, Opedal *et al.*, 2015, de Boeck *et al.*, 2016). Many species indeed survive, live and reproduce where average background climate appears unsuitable, and equally may be gone from sites within apparently suitable

82 areas where microclimatic extremes exceed their limits (Suggitt *et al.*, 2011). Without microclimate data,  
83 we not only lack information on the potential thermal heterogeneity that is available for species to  
84 thermoregulate in situ, but also on the true magnitude of climate change that species will be exposed to  
85 (Pincebourde *et al.*, 2016, Maclean *et al.*, 2017). Accurately predicting how species' ranges will shift under  
86 climate change requires a good understanding of the variety of climate niches truly available to them  
87 (Maclean *et al.*, 2015, Lenoir *et al.*, 2017). The latter requires both a good understanding of what defines  
88 current microclimates, as well of how climate change will interact with the drivers of microclimatic  
89 conditions (Maclean, 2019). Additionally, it is the soil temperature rather than the air temperature that  
90 defines many ecosystem functions in and close to the soil, like evapotranspiration, decomposition, root  
91 growth, biogeochemical cycling and soil respiration (Pleim & Gilliam, 2009, Portillo-Estrada *et al.*, 2016,  
92 Hursh *et al.*, 2017, Gottschall *et al.*, 2019, Medinets *et al.*, 2019). Given the repeatedly proven sensitivity  
93 of many of these processes to temperatures (Rosenberg *et al.*, 1990, Coûteaux *et al.*, 1995, Schimel *et al.*,  
94 1996), here again having accurate measurements will be of utmost importance. The carbon balance in  
95 boreal forests, for example, is largely dependent on soil thaw and thus soil rather than air temperatures  
96 (Goulden *et al.*, 1998).

97 These realizations highlight the urgency to start using soil and near-surface microclimate data when  
98 modelling the ecology and biogeography of surface and soil-dwelling organisms, as well as the functioning  
99 of soil ecosystems, instead of readily available coarse-scaled free-air climate data (from e.g. CHELSA  
100 (Karger *et al.*, 2017), TerraClimate (Abatzoglou *et al.*, 2018) or WorldClim (Fick & Hijmans, 2017)). While a  
101 suit of models now exist that produce fine-scale climate data (Bramer *et al.*, 2018, Lembrechts *et al.*,  
102 2018), we do not yet fully understand whether models using data that represent average conditions over  
103 large areas provide adequate “mean field approximations” of (i.e. are representative for) more complex  
104 spatiotemporal effects driven by the climatic conditions that organisms experience (Bennie *et al.*, 2014).  
105 To accomplish the latter, global in-situ data is needed for large-scale fine-resolution calibration and  
106 validation of these models. However, while the quality and resolution of free-air temperature data and  
107 models at the global scale is rapidly improving (Bramer *et al.*, 2018), soil temperature datasets used in  
108 biogeography and biogeochemistry are still largely restricted to the landscape or regional scale, at best,  
109 and from intensively studied regions only (Ashcroft *et al.*, 2008, Ashcroft *et al.*, 2009, Carter *et al.*, 2015,  
110 Aalto *et al.*, 2018), or they are derived from models lacking fine-grained ground-truthing data (e.g.  
111 Copernicus Climate Change Service (C3S), 2019). Land surface temperatures as obtained from satellite  
112 data, on the other hand, are hampered by their inability to measure below the vegetation cover (Bramer  
113 *et al.*, 2018).

114 In order to accurately describe and predict the (future) distribution and/or traits of surface and soil-  
115 dwelling species at larger scales, we need to improve our general knowledge of the offsets and  
116 spatiotemporal changes in variability between soil-level and free-air temperatures (Aalto *et al.*, 2018,  
117 Lembrechts *et al.*, 2019). There is an urgent need to work towards globally available soil and near-surface  
118 temperature data based on in-situ measurements and at relevant spatiotemporal resolutions (Ashcroft &  
119 Gollan, 2012, Pradervand *et al.*, 2014, Slavich *et al.*, 2014, Opedal *et al.*, 2015, Meineri & Hylander, 2017).

## 120 ***Launch of the SoilTemp database***

121 To tackle these issues, we launch an ambitious database initiative, compiling soil and near-surface  
122 temperature data from all over the world into a global geospatial database: SoilTemp. At the time of  
123 writing, we brought together temperature data from 7538 sensors placed both below, at and above (up to  
124 2 m) the soil surface (Fig. 2a), which is an accumulation of over 180.000 months of temperature data with  
125 measurement intervals between 1 and 240 minutes (>30% every 60 minutes). The database hosts loggers  
126 from 51 different countries spread across all continents, with a broad distribution across the world's  
127 climatic space (Fig. 2b). There is a dominance of time series from Europe and areas below 1500 m a.s.l.  
128 (Fig. 2c, d). More than 75% of sensor measurements occurred within the last decade, but the database  
129 does contain several time series covering longer time periods as well, with a maximum of 42 years (Fig.  
130 2d).

131 When the remaining critical gaps in our spatial coverage will be filled (see below), this database will allow  
132 global assessments of the long-established theories on boundary layer climatology in heterogeneous  
133 environments (Geiger, 1950), which has so far been lacking. The growing database provides a unique  
134 opportunity to disentangle the role of the different horizontal and vertical features influencing soil and  
135 near-surface temperature across all biomes of the world, with high spatial and temporal resolutions. It  
136 will allow relating patterns in soil temperature to processes in the lower air layers and calibrate and  
137 validate global models of soil temperature and (micro)climate (Kearney *et al.*, 2014a, Kearney *et al.*,  
138 2014b, Carter *et al.*, 2015, Maclean *et al.*, 2017). It will also allow us to create global maps of a wide array  
139 of general and microclimate-specific bioclimatic variables (e.g. growing degree days, growing season  
140 length) at relevant spatiotemporal resolutions (Körner & Hiltbrunner, 2018).

141 Ultimately, this joint global effort and the resulting global microclimatic products will enable us to  
142 improve analyses of the relationships between species' macroecology and the microclimate they  
143 experience, identify microrefugia and stepping stones and improve global models of ecosystem  
144 functioning and element cycling. Indeed, replacing the coarse-scaled free-air temperature averages used

traditionally in models in all fields of ecology with these more relevant soil-specific data products is likely to increase their descriptive and predictive power, as the countless above-mentioned regional studies exemplify (Lembrechts *et al.*, 2019). Additionally, this first global effort to combine and collect in-situ measurements will help solve long-standing issues regarding sensor comparability and data collection variability (Bramer *et al.*, 2018), as well as address the question at what spatial scale microclimate data can prove most informative for ecological modelling (Jucker *et al.*, 2020). The temperature time series in the database, many of which are covering increasingly long time periods of up to a decade or more, will also allow fine-tuning forecasts of microclimate data into the future by deepening our understanding of the link between microclimatic dynamics in the soil and the air (Lenoir *et al.*, 2017, Wason *et al.*, 2017, Bramer *et al.*, 2018, Maclean, 2019), improving our predictions of biodiversity and ecosystem functioning under climate change.

#### ***Dig out your loggers! A call for contributions***

To reach these goals, we encourage scientists owning in-situ measured temperature data to submit these to the growing SoilTemp database. All time series spanning one month or more, with temperature measurements a maximum of 4 hours apart, all soil depths, all heights above the ground up till two meters, all biomes, and all sensor types and brands will be accepted. Note that both spatially dense and sparse logger networks, as well as single loggers are accepted. The achieved spatial resolution is dependent on the provision of spatially precise coordinates to achieve a good relationship with potential explanatory variables (e.g. high resolution remotely sensed environmental data). If we have these coordinates and thus the location and distance between loggers, we can effectively obtain the extent and spacing for each logger network (Western *et al.*, 2002).

We include data from both observational and experimental plots, yet sensors have to be measuring in-situ and not in pots, and experiments manipulating the local climate (e.g. open-top chambers, rain-out shelters or vegetation-removal experiments) are excluded (Table 1). Given currently less well-represented climate regions, we especially encourage submissions from extreme cold and hot environments to fill the remaining gaps in our global coverage. More specifically, hot tropical climates (both tropical rainforests and tropical seasonal forests and savannas) and cold and hot deserts are currently still largely underrepresented (Fig. 2b), in particular from Africa, Asia, Antarctica and the Americas (Fig. 2a). Data contributors will be invited as co-authors on the main global papers resulting from this database (see Supplementary Materials for details on terms of use and data ownership).



175 By encouraging sampling and submissions from remote areas, we aim to help solve the global sampling  
176 bias in soil ecological data (Cameron *et al.*, 2018, Guerra *et al.*, 2019), and we hope to build a truly global  
177 network representing – and actively engaging - scientists from a wide diversity of cultural backgrounds  
178 (Maestre & Eisenhauer, 2019). More information is available on the SoilTemp website, accessible via  
179 Figshare (DOI 10.6084/m9.figshare.12126516).

180 When fully established, the SoilTemp database and its derivative products (e.g. bioclimatic variables) will  
181 be made freely available to facilitate the analysis of global patterns in microclimates, increase the  
182 comparability between regional studies and simplify the use of accurate microclimatic data in ecology  
183 (Bramer *et al.*, 2018). At the moment, critical metadata is already freely accessible via Figshare (DOI  
184 10.6084/m9.figshare.12126516). Given the absence of and the need for globally available soil  
185 microclimate data products at relevant spatial resolutions for use in ecological analyses, we believe that  
186 SoilTemp has the potential to become a highly important resource that will enable a step change in  
187 ecological modelling.

188

189 **Table**

190 *Table 1: Minimal data requirements and obligatory metadata for submission to the database. For more*  
191 *details, see Supplementary Material.*

192

| Minimum data requirements   | Obligatory metadata   |
|---|---|
| Minimum one consecutive month of in-situ measured temperature time series                               | Accurate (handheld GPS or finer) spatial coordinates of the loggers (+ estimated accuracy)                              |
| Maximum time interval between measurements: 4 hours   | Height/depth of the sensor relative to the soil surface   |
| No climate manipulation experiments (only control plots of those experiments, or observational studies) | Type or brand of temperature sensor used, and type of shelter (e.g. no shelter, home-made shelter, Stevenson screen...) |
| No modelling studies (only empirical data)  | Temporal resolution of the sensor   |
|   | Habitat classification  |

193

194

196 **Figure 1: The horizontal and vertical drivers of the offset between in-situ soil and free-air temperatures.**

197 Conceptually, there are two different sets of features responsible for the offset between coarse-scale free  
198 air temperatures (top left, e.g. WorldClim, Fick & Hijmans, 2017) and fine-scale soil temperatures (bottom  
199 right, e.g. Ashcroft & Gollan, 2012, Lembrechts et al., 2019),. Firstly, one can incorporate fine-scale  
200 horizontal climate-forcing factors like topography and terrain-related features, land cover types and  
201 distance to water bodies to go from coarse-scaled to finer resolutions (top right, e.g. Aalto et al., 2017,  
202 Macek et al., 2019). Secondly, one can consider observation height, and the effects of vegetation  
203 characteristics (like structure and cover), snow cover and soil characteristics (like moisture, geological  
204 types, texture and bulk density) on the radiation balance to convert from free-air to soil temperatures (e.g.  
205 Kearney, 2019). Both horizontal and vertical features can introduce positive or negative differences (offset  
206 values) between soil and air temperatures through their effects on processes related to the radiation  
207 balance, like wind, convective heat transfer and surface albedo. The complexities of these horizontal and  
208 vertical processes can vary with biome, season and time of day. Temperatures are represented here using  
209 an unspecified temperature range from cold (blue) to warm (red).

**Figure 2: Overview of the status of the SoilTemp-database as of March 2020.** Spatial (a), climatic (b), elevational (c) and temporal (d) distribution of sensors in the SoilTemp-database as of March 2020. (a) Background world map in WGS1984, hexagons with a resolution of approximately 70.000 km<sup>2</sup> using the *dggridR*-package in R. (b) Colors of hexagons indicate the number of sensors at each climatic location, with a 40 × 40 bin resolution. Small dots in the background represent the global variation in climatic space (obtained by sampling 1.000.000 random locations from the CHELSA world maps at a spatial resolution of 2.5 arc minutes. Overlay with dotted lines and numbers (from 1 to 9) depict a delineation of Whittaker biomes (adapted from Whittaker, 1970): (1) tundra and ice, (2) boreal forest, (3) temperate seasonal forest, (4) temperate rainforest, (5) tropical rainforest, (6) tropical seasonal forest/savanna, (7) subtropical desert, (8) temperate grassland/desert, (9) woodland/shrubland. (c) Number of sensors in each elevation class. (d) Time span covered by each sensor in the database, ranked by starting date. Data showed from 1992 onwards, note that the time period covered by 4 loggers with starting dates in 1976 is truncated.

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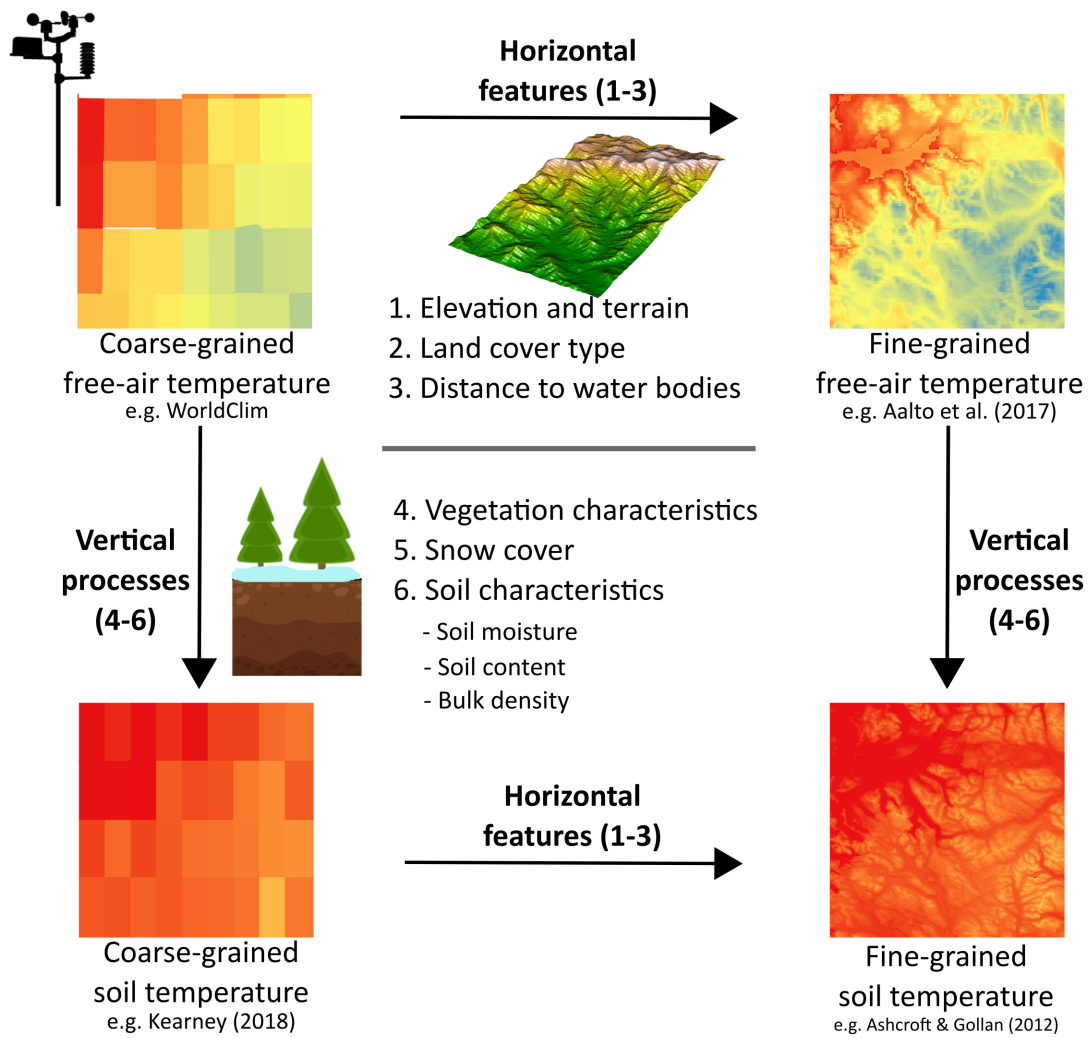
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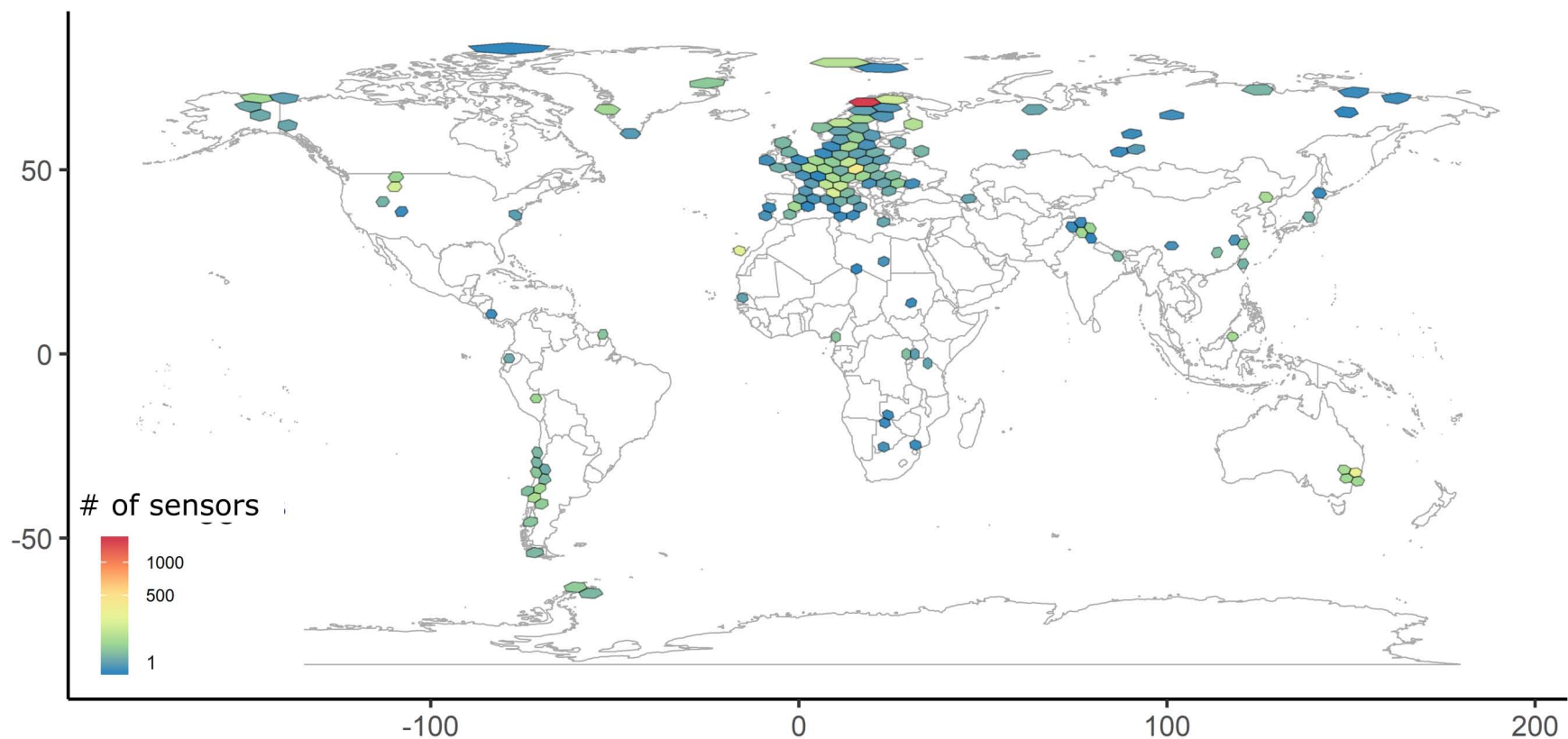
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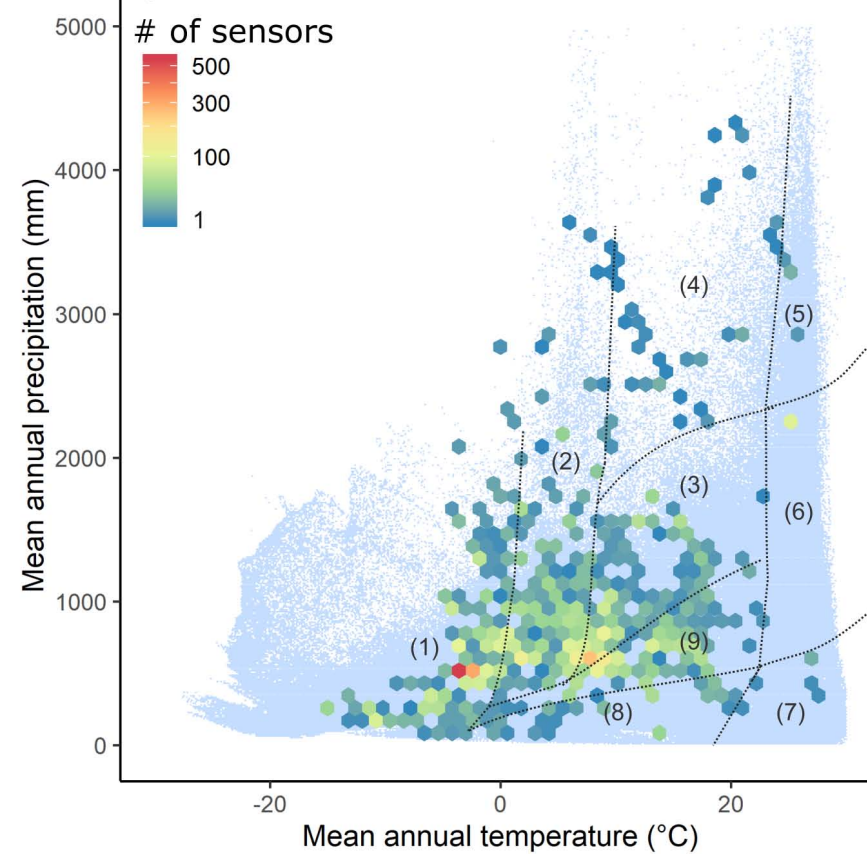


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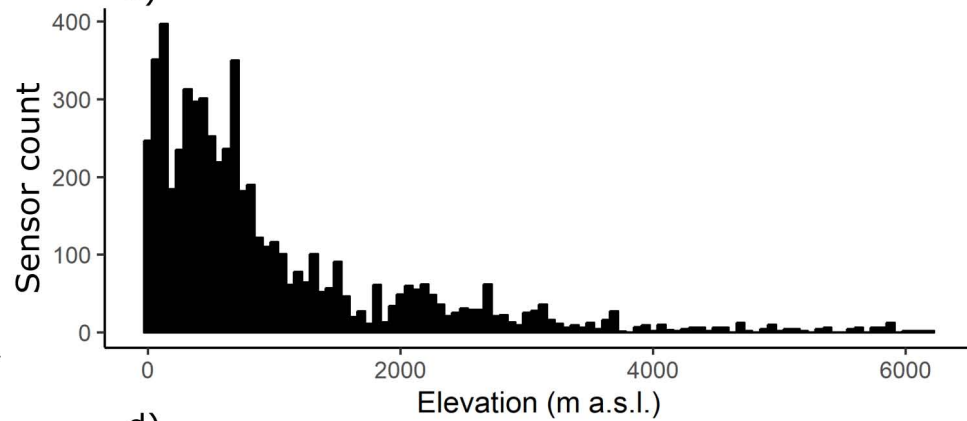
a)



b)



c)



d)

