

UCRL-JRNL-225506



LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Nano-Scale Secondary Ion Mass Spectrometry - A new analytical tool in biogeochemistry and soil ecology

A. M. Herrmann, K. Ritz, N. Nunan, P. L. Clode, J. Pett-Ridge, M. R. Kilburn, D. V. Murphy, A. G. O'Donnell, E. A. Stockdale

October 23, 2006

Soil Biology and Biochemistry

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

1 Type of contribution: Special edition: Molecular approaches
2 Date of preparation: 30 October 2006
3 Number of text pages: 46
4 Number of tables: 1
5 Number of figures: 6

6 Nano-scale secondary ion mass spectrometry – a new analytical tool
7 in biogeochemistry and soil ecology

8 Names of authors: Anke M. Herrmann^{1,6*}, Karl Ritz², Naoise Nunan³, Peta L.
9 Clode⁴, Jennifer Pett-Ridge⁵, Matthew R. Kilburn⁴, Daniel V.
10 Murphy¹, Anthony G. O'Donnell⁶, Elizabeth A. Stockdale⁷

11 ¹School of Earth and Geographical Sciences, The University of Western Australia, 35
12 Stirling Highway, Crawley, WA 6009, Australia.

13 ²National Soil Resources Institute, School of Applied Sciences, Cranfield University,
14 Cranfield, MK43 0AL, U.K.

15 ³CNRS, UMR BioEMCo, Institut National Agronomique Paris-Grignon, Bâtiment
16 EGER, 78850 Thiverval-Grignon, France.

17 ⁴The Centre for Microscopy and Microanalysis, The University of Western Australia,
18 35 Stirling Highway, Crawley, WA 6009, Australia.

19 ⁵Lawrence Livermore National Laboratory, P.O. Box 808, L-231, Livermore, CA
20 94551-9900, USA.

21 ⁶Institute for Research on Environment and Sustainability, Devonshire Building,
22 University of Newcastle, Newcastle upon Tyne, NE1 7RU, U.K.

23 ⁷School of Agriculture, Food and Rural Development, King George VI Building,
24 University of Newcastle, Newcastle upon Tyne, NE1 7RU, U.K.

25 * Corresponding author: Anke M. Herrmann

26 Present address:

27 School of Earth and Geographical Sciences
28 The University of Western Australia
29 35 Stirling Highway
30 Crawley, WA 6009
31 Australia

32 Tel.: + 61 - 8 - 6488 1884

33 Fax: + 61 - 18 - 6488 1050

34 E-mail address: Anke.Herrmann@newcastle.ac.uk

35 **Abstract**

36 Soils are structurally heterogeneous across a wide range of spatio-temporal scales.
37 Consequently, external environmental conditions do not have a uniform effect
38 throughout the soil, resulting in a large diversity of micro-habitats. It has been
39 suggested that soil function can be studied without explicit consideration of such fine
40 detail, but recent research has indicated that the micro-scale distribution of organisms
41 may be of importance for a mechanistic understanding of many soil functions. Due to
42 a lack of techniques with adequate sensitivity for data collection at appropriate scales,
43 the question ‘How important are various soil processes acting at different scales for
44 ecological function?’ is challenging to answer. The nano-scale secondary ion mass
45 spectrometer (NanoSIMS) represents the latest generation of ion microprobes which
46 link high-resolution microscopy with isotopic analysis. The main advantage of
47 NanoSIMS over other secondary ion mass spectrometers is the ability to operate at
48 high mass resolution, whilst maintaining both excellent signal transmission and spatial
49 resolution (~50 nm). NanoSIMS has been used previously in studies focusing on
50 presolar materials from meteorites, in material science, biology, geology and
51 mineralogy. Recently, the potential of NanoSIMS as a new tool in the study of
52 biophysical interfaces in soils has been demonstrated. This paper describes the
53 principles of NanoSIMS and discusses the potential of this tool to contribute to the
54 field of biogeochemistry and soil ecology. Practical considerations (sample size and
55 preparation, simultaneous collection of isotopes, mass resolution, isobaric interference
56 and quantification of the isotopes of interest) are discussed. Adequate sample
57 preparation avoiding biases in the interpretation of NanoSIMS data due to artefacts
58 and identification of regions-of interest are of most concerns in using NanoSIMS as a
59 new tool in biogeochemistry and soil ecology. Finally, we review the areas of research

60 most likely to benefit from the high resolving power attainable with this new
61 approach.

62 **1. Introduction**

63 Soils are highly complex porous media that are structurally heterogeneous across a
64 wide range of spatio-temporal scales (Tisdall and Oades, 1982; Young and Ritz,
65 1998). Their organisation at the micro-scale results in a range of micro-habitats that
66 exert differential selection pressures on microbial communities, both governing and
67 sustaining the huge microbial diversity in soil (Ranjard et al., 2000b; Treves et al.,
68 2003; Mummey and Stahl, 2004; Long and Or, 2005; Nunan et al., 2006). Micro-
69 organisms mediate a vast range of reactions in soil, and fine-scale interactions
70 between micro-organisms and the physical, chemical and other biotic components of
71 the soil environment control or modulate these reactions (Sierra et al., 1995; Strong et
72 al., 1997; Chenu et al., 2001; Ranjard et al., 2000a; Young and Crawford, 2004).
73 Understanding of these relationships is complicated by the fact that interactions
74 among the various components of the soil system are often scale-dependent (Ettema
75 and Wardle, 2002), meaning that factors that greatly influence soil micro-organisms
76 and soil function at a given scale may be of lesser importance at other scales. Soil
77 biologists are therefore confronted with the issue of how to deal both conceptually and
78 experimentally with such a high degree of diversity and array of interactions.

79 There are cogent arguments that suggest reductionist approaches that explicitly
80 accommodate the inherent complexity of soils are not necessary to understand the
81 controlling factors of many soil functions, nor to predict their magnitude and
82 behaviour. So-called ‘averaging engine’ approaches have been successful, showing
83 that it is possible to model and understand overall function without resorting to fine

84 detail; an analogy is the gas box where the pressure a gas exerts can be accurately
85 predicted without knowledge of the trajectory of every atom (Andrén et al., 1999).
86 Likewise, gross process rates arising from community-level activity in soil can be
87 predicted (Hart et al., 1994; Bengtsson et al., 2003; Herrmann et al., 2004). However,
88 more sophisticated predictions, for example where a number of environmental, soil
89 physical, chemical and biotic factors change simultaneously are considerably less
90 reliable. The crucial difference between the constituents in the soil biota and a gas is
91 that the component parts in soil are *individually adaptive* (over time-scales ranging
92 from instantaneous to evolutionary), and the interactions between them are likely to
93 be complex rather than just following ‘simple’ physical laws such as Brownian
94 motion. Interactions among constituents may therefore have important consequences
95 for function at larger scales that cannot be inferred from a mere inventory of the
96 constituents and integration of their individual properties. Large scale properties
97 relevant to soil function at field, catchment or regional scale may arise from
98 interactions among individual parts, a phenomenon termed emergent behaviour. For
99 example, a process such as horizontal gene transfer (van Elsas and Bailey, 2002;
100 Sørensen et al., 2005) cannot be easily explained by gross process-level phenomena
101 and there are examples in the literature where averaging approaches do not perform
102 well (e.g. ammonium oxidation; Darrah et al., 1987). In other words, the origin,
103 evolution, maintenance and control of function in soils as well as their capacity to
104 adapt is likely to depend upon mechanisms and interactions that *fundamentally occur*
105 at size scales of the range from molecular to microbial (Crawford et al., 2005).

106 An important challenge for soil research is to establish both (i) how the hierarchy of
107 processes and mechanisms that occur contribute to ecosystem function and (ii) the
108 scales at which these operate. The question ‘How important are the various processes

109 acting at different scales for ecological function in soils?’ cannot be answered in most
110 cases with any degree of certainty. A major obstacle to progress is the lack of
111 techniques with adequate sensitivity for data collection at appropriate (i.e. microbial)
112 scales. For example, most biochemical-based techniques for studying nutrient cycling
113 and micro-organism:plant nutrient transfers are applied at scales several orders-of-
114 magnitude greater (i.e. cm and mm, grams of soil) than at the cellular scale at which
115 the processes actually occur (Figure 1). For example, the average concentration of a
116 heavy metal in a 100-g soil sample may bear little relation to the concentrations of the
117 metal that micro-organisms may experience at the micro-scale, which could range
118 from effectively zero in some micro-sites, to very high in the proximity of metal
119 particles.

120 Soils predominantly function by virtue of their spatial organisation. This has been,
121 and often still is, ignored in their study, where experimental approaches seek to
122 homogenise the ‘inconvenience’ of heterogeneity. But this is a wilful avoidance of a
123 crucial feature, which was eloquently articulated some seven decades ago by Kubiena
124 (1938), who stated ‘*Take, for instance, a city. If it were put in a large glass vessel with*
125 *water or hydrochloric acid, as we do with the soil, and shaken for twenty-four hours,*
126 *one would not then be able to reconstruct streets or buildings, or to find out what kind*
127 *of goods are found in the large warehouse. The first thing to know, in order to get an*
128 *idea of the city, is not much the nature of its chemical composition as a whole, but*
129 *how it looks in detail as a structural entity.*’ Other authors have since reiterated this
130 rather obvious point (e.g. Harris, 1994; Wardle and Giller, 1996; Young and Ritz,
131 2005). But whilst soils function by virtue of their architecture, across scales from
132 nano- to mega-metres, study at the smallest scales is hampered by available
133 technology and methodology. Following Kubiena’s pioneering work on soil micro-

134 morphology and that of soil ultra-structure using electron microscopy by Foster in the
135 1970's and 1980's (Foster and Rovira, 1973; Foster and Martin, 1981; Foster et al.,
136 1983), there have been continued technological and methodological advances
137 involving optical microscopy (e.g. Nunan et al., 2001), scanning (e.g. Chenu and
138 Tessier, 1995) and transmission electron microscopy (e.g. Kilbertus, 1980; Chenu and
139 Plante, 2006), X-ray tomography (e.g. De Gryze et al., 2006; Feeney et al., 2006;
140 Nunan et al., 2006), and spatial statistics and modelling (e.g. Young et al., 2001;
141 Grundmann et al., 2001; Wu et al., 2004).

142 A new generation of ion microprobes, nano-scale secondary ion mass spectrometers
143 (NanoSIMS) is emerging, which allows precise, spatially-explicit, elemental and
144 isotopic analysis at the nm scale. These instruments have been applied to studies of
145 presolar materials from meteorites (For reviews, see Hoppe et al., 2004; Hoppe,
146 2006), in material science (e.g. Kailas et al., 2006), geology and mineralogy (e.g.
147 Stern et al., 2005) as well as biology (For reviews, see Guerquin-Kern et al., 2005;
148 Grovenor et al., 2006), and offer many exciting opportunities for potential application
149 within the field of biogeochemistry and soil ecology. This paper describes the
150 principles of such an instrument, provides an overview of NanoSIMS applications,
151 and reviews the challenges and further opportunities for the application of NanoSIMS
152 as an analytical tool to increase resolution and understanding of microbial processes
153 in soil.

154 **2. Principles of NanoSIMS**

155 Secondary ion mass spectrometry (SIMS) is an ion microprobe technology linking
156 high resolution microscopy with isotopic analysis, providing spatially resolved
157 information on the molecular and isotopic compositions of materials (Pacholski and

158 Winograd, 1996). The basis for the technique was introduced in the 1960's by
159 Castaing and Slodzian (1962), and two types of SIMS are available, defined as static
160 and dynamic. Static SIMS is typically used to attain molecular and fine surface
161 information (less than 1 nm depth) whereas dynamic SIMS is routinely used to
162 acquire elemental and isotopic information from the upper few nm of the sample (for
163 further details see Pacholski and Winograd, 1999; Adams et al., 2005). The Cameca
164 NanoSIMS50[®] (Slodzian et al., 1992) currently represents the latest generation of ion
165 microprobes designed for dynamic SIMS and its advantages over other SIMS
166 instruments are given in Table 1. The prototype instrument was installed at Harvard
167 Medical School and Brigham and Women's Hospital (Boston, USA) in early February
168 1999. By mid-2006 another 14 instruments have subsequently been installed around
169 the world. An overview of the development of SIMS instruments is given in
170 Guerquin-Kern et al. (2005).

171 NanoSIMS is a destructive process that involves continuous bombardment of a
172 sample with an energetic ion beam (either a Cs⁺ or O⁻ primary beam to enhance
173 negative or positive ion formation, respectively), which results in sputtering of the
174 upper sample surface and the consequent liberation of secondary ions (Figure 2).
175 These secondary ions are sorted on the basis of their energy in the instrument's
176 electrostatic sector before being dispersed in a mass spectrometer according to their
177 mass-to-charge ratios. By acquiring a series of spatially-referenced spectra, via a
178 raster-scanning process, a map can be produced for nearly any selected atomic mass,
179 and information of isotopic ratios in the form of regions-of-interest, line scans and
180 depth profiling can be obtained. The system is maintained permanently under ultra-
181 high vacuum to prevent atmospheric interference with primary and secondary ions
182 (typically 10⁻¹⁰ Torr in the analysis chamber).

183 **3. Applications of NanoSIMS**

184 *3.1. Previous NanoSIMS applications*

185 To date, NanoSIMS has been principally applied to the study of presolar material
186 from meteorites, using trace element analysis and natural isotopic abundances (e.g. C,
187 N, O, Mg/Al, Si and S), in order to determine the physical and chemical conditions of
188 processes in the early solar system (e.g. Messenger et al., 2004; Floss et al., 2004;
189 Hoppe et al., 2004; Bradley et al., 2005; Floss et al., 2006). NanoSIMS has also been
190 used with some success to study the surface morphology and composition of thin film
191 polymer systems (Kailas et al., 2005; Kailas et al., 2006) and in studies in biology
192 (Guerquin-Kern et al., 2005; Grovenor et al., 2006). Specifically in biology,
193 NanoSIMS has been used to detect both natural and isotopically-enriched elemental
194 and isotopic variations in coral (Meibom et al., 2004; Sano et al., 2005; Clode et al.,
195 2007) and hair melanin (Hallegot et al., 2004) and to study sub-cellular uptake of an
196 ¹²⁵I-labelled drug by cancer cells (Guerquin-Kern et al., 2004). NanoSIMS has also
197 provided information on C and N metabolism in cultured cells using ¹³C and ¹⁵N as
198 isotopic tracers (Peteranderl and Lechene, 2004; Kleinfeld et al., 2004). More recently
199 it has been used to study the chemical composition of lipid membranes (Kraft et al.,
200 2006). Earth scientists have also successfully utilised the technique to study lead
201 geochronology in minerals such as xenotime, zirconite and uraninite (Stern et al.,
202 2005), isotope exchange between feldspar and aqueous chloride solution (Labotka et
203 al., 2004) and trace element distribution in peridotites (Hellebrand et al., 2005).

204 3.2. Proof-of-concept: Application of NanoSIMS in soil

205 As soil is a medium where geological and biological materials are combined
206 intimately, NanoSIMS potentially offers a range of advantages for biogeochemistry
207 and soil ecology (Table 1). Pioneering work in the application of SIMS to soils (Cliff
208 et al. 2002a) showed that it was possible to qualitatively describe the assimilation of
209 added ^{15}N and ^{13}C into soil micro-organisms *in situ*, using time-of-flight secondary
210 ion mass spectrometry (TOF-SIMS). Their results suggest that SIMS shows promise
211 as a tool for studying soil micro-habitat heterogeneity and microbial activity in
212 combination. While the advantages of TOF-SIMS include the ability to acquire
213 molecular and true isotopic surface information, these data cannot be acquired under
214 conditions suitable for obtaining both high mass (i.e. peak separation of elements with
215 similar masses) and high spatial resolution with adequate signal transmission. Any
216 attempt at increasing mass resolution to ensure separation of isobars or mass
217 interferences will result in a loss of spatial resolution and signal transmission.
218 Conversely, conditions designed to allow for increased signal transmission or
219 improved spatial resolution will result in a decline in the operating mass resolution of
220 the instrument. For example, Cliff et al. (2002a) used very high beam currents (600
221 pA) in order to obtain sufficient mass resolution and signal, which meant they could
222 not achieve a high level of spatial resolution (< 200 nm). The main advantage of
223 NanoSIMS over TOF-SIMS is the ability of NanoSIMS to operate at high mass
224 resolution, whilst maintaining both excellent signal transmission (i.e. increased
225 sensitivity) and high spatial resolution (Table 1).

226 A recent study by Herrmann et al. (2007) showed that NanoSIMS can be used to
227 detect isotopically enriched bacterial cells in the soil matrix. This was achieved by
228 adding ^{15}N enriched *Pseudomonas fluorescens* grown in a mineral salt medium

229 containing ^{15}N -ammonium sulphate to a coarse textured sand soil. The soil cores were
230 embedded in Araldite resin and sectioned for NanoSIMS analysis. To allow the study
231 of biophysical interactions in soils at relevant scales, ion distribution images of $^{28}\text{Si}^-$,
232 $^{12}\text{C}^{14}\text{N}^-$ and the $^{15/14}\text{N}$ ratio data were superimposed using image processing software
233 and mosaics of ion images were made. The mapping procedure, utilising secondary
234 ion images of $^{12}\text{C}^-$, $^{28}\text{Si}^-$, $^{12}\text{C}^{14}\text{N}^-$ and $^{15/14}\text{N}$ ratios revealed the location of ^{15}N -labelled
235 *P. fluorescens* in coarse textured sand (Figure 3; full details of the methods can be
236 found in Herrmann et al., 2007). The resin distribution was revealed by the $^{12}\text{C}^-$ ion
237 image (Fig. 3a) as the resin was inevitably carbon-based, while the $^{28}\text{Si}^-$ ion image
238 provided information on the soil matrix (Fig. 3b). Nitrogen-rich organic matter was
239 also clearly visible in the $^{12}\text{C}^{14}\text{N}^-$ ion image (Fig. 3c), and the distribution and level of
240 ^{15}N enriched *P. fluorescens* were revealed in the $^{15/14}\text{N}$ ratio image (Fig. 3d). When
241 secondary ion images of $^{28}\text{Si}^-$, $^{12}\text{C}^{14}\text{N}^-$ and those of the $^{15/14}\text{N}$ ratio data were
242 superimposed (Figure 4) the potential of the technique in enabling small-scale study
243 of bacteria in soil and their biophysical interactions is apparent (Herrmann et al.,
244 2007).

245 **4. Practical considerations in the use of NanoSIMS for soil studies**

246 Despite recent technological progress, there are several practical issues to be
247 considered if NanoSIMS is to be used as a component method in a study of
248 biogeochemistry or soil ecology. Key issues include sample size and preparation,
249 simultaneous collection of isotopes, mass resolution, isobaric interference and
250 quantification of the isotopes of interest.

251 4.1. Sample size and preparation

252 Samples presented for analysis by NanoSIMS must be dry, stable, conductive and
253 tolerant of ultra-high vacuum (10^{-10} Torr). In addition, soil samples should ideally be
254 flat and highly polished with no more than nm-level variations in surface topology as
255 charging effects (i.e. obscuring the boundaries between mineral and organic particles)
256 are likely to occur when analysing soil particles without specific sample preparation
257 (Figure 5a). Gold coating in combination with the use of the electron flood gun can
258 lessen such charging effects (Figure 5b). In this example, whilst regions of higher C
259 enrichment are evident, the nature of this material (minerals, soil organic matter or
260 micro-organisms) cannot be identified due to charging effects. As such, it appears
261 critical to produce embedded soil sections that can be polished and made conductive.
262 Usually sample preparation involves stabilisation of biological components (fixation),
263 removal of water (dehydration) and resin-embedding of soil. These requirements
264 therefore prohibit the study of material in any aqueous phase and hence restrict
265 application of imaging ion mass spectrometry outwith dynamic *in vivo* studies, as
266 preparation of samples for analysis is necessarily destructive. However, resin-based
267 techniques for preparing undisturbed soil samples are well characterised and proven,
268 and have been routinely used to study the small-scale distribution of micro-organisms
269 in soils (Postma and Altemüller, 1990; Tippkötter and Ritz, 1996; Fisk et al., 1999;
270 Nunan et al., 2003; Harris et al., 2003; Bruneau et al., 2005).

271 Fixation and dehydration of biological tissues is typically carried out either by
272 chemical means (fixation followed by dehydration with acetone; Tippkötter and Ritz,
273 1996; Nunan et al., 2001) or low temperature methods (rapid freezing followed by
274 freeze drying or substitution; Chandra et al., 1992; Echlin, 1992). Chemical fixation
275 was shown to be a suitable method for studying ^{15}N accumulation in *P. fluorescens*

276 mixed into a coarse textured sand (Herrmann et al., 2007). However only 35% of
277 photosynthetically fixed ^{13}C was retained as protein in symbiotic algae, following
278 chemical fixation in a glutaraldehyde:paraformaldehyde mixture (Clode and Marshall,
279 unpublished data). In studies where significant migration of the element(s) of interest
280 is likely to occur during sample preparation, low temperature methods such as freeze-
281 drying offer a more promising solution. This method has been reliably used to study
282 ^{13}C and ^{15}N metabolism in cultured cells using NanoSIMS (Peteranderl and Lechene,
283 2004). There are, however, several limitations to cryo-techniques, particularly in
284 relation to soils. Of most concern is the satisfactory freezing of biological material
285 within bulk soil samples. Adequate quality of freezing only extends to depths
286 typically in the order of μm , beyond this, damage induced by ice crystals is severe
287 (Echlin, 1992). Thus, sufficient preservation of soil samples and their associated
288 micro-organisms is unlikely to be routinely achievable using cryo-techniques.

289 To date, the epoxy resin Araldite 502 has proven to be the most suitable resin-
290 embedding medium among three different resin brands trialled (Herrmann et al.,
291 2007), as it gave the most rapid outgassing (i.e. trapped and adsorbed gas in the
292 samples has to be released, to enable pumping to the high vacuum required for
293 NanoSIMS analysis). This resin contains carbon with ^{13}C at natural abundance
294 (ProSciTech, Australia), therefore $^{13}/^{12}\text{C}$ ratios may not be indicative of true ratios of
295 ^{13}C enriched material in the sample. However, the ratio provides a semi-quantitative
296 indication of the level of enrichment above natural levels, and accounts for any
297 variation in ion yield due to topographical and matrix effects. Furthermore, ^{12}C
298 distribution can also be used to visualise resin distribution (Herrmann et al., 2007). An
299 alternative could be the use of elemental sulphur as an embedding medium. However,
300 only very small samples can be prepared and analysed by this means. Lehmann et al.

301 (2005) restricted study of biomass-derived black C particles to those with a diameter
302 of 5-80 μm , as the optimum consistency of the sulphur for embedding lasts for only
303 10-30 seconds.

304 In the ultra-high vacuum environment of the NanoSIMS, Herrmann et al. (2007)
305 found that samples must be < 4 mm thick in order to avoid outgassing issues (see
306 above). Furthermore, the most suitable NanoSIMS sample mounts for soil analysis
307 appear to be the 10 mm diameter mounts as up to eight samples can be placed into the
308 analysis chamber at any one time. A larger (25 mm diameter) mount could also be
309 used, but very thin samples are needed to avoid outgassing issues and it must be borne
310 in mind that only one sample can be placed into the analysis chamber at any one time.
311 The most appropriate sample preparation method will always be dependent upon the
312 sample size and type, the level of retention and migration of the element(s) of interest
313 during sample preparation together with the specific question to be addressed by the
314 NanoSIMS analysis.

315 *4.2. Simultaneous collection of isotopes*

316 The NanoSIMS is able to detect up to five ion species at one time (Table 1), allowing
317 simultaneous measurement of two to five isotopes from the same micro-volume of
318 sputtered material. This is particularly important in samples that are susceptible to
319 damage from the primary ion beam, where low concentrations of ions may be rapidly
320 destroyed in a small volume of material. As mentioned above, negative secondary
321 ions are sputtered using a Cs^+ primary ion beam (lateral resolution = of 50 nm), and
322 positive secondary ions are sputtered using an O^+ primary ion beam (lateral resolution
323 = 150 nm). Nitrogen ions, as well as elements in Group VIII of the Periodic Table, do
324 not ionise easily and therefore do not produce enough secondary ions to be detected.

325 However, ejected N ions combine with C ions to form cyanide ions (CN⁻), which can
326 be readily detected. These CN⁻ ions have extremely high electron affinity (3.9 eV;
327 Bradforth et al., 1993), thus the yield of secondary CN⁻ is particularly high.

328 Simultaneous analysis of ion species is, however, limited. The physical separation of
329 the detectors is limited by the radius of secondary ion trajectories (R) (Figure 2),
330 which is dependent on the magnetic field. Up to mass 30, one mass interval between
331 the detectors can be analysed simultaneously, i.e. it is possible to analyse ¹²C⁻ and ¹³C⁻
332 or ¹⁶O⁻, ¹⁷O⁻, ¹⁸O⁻ or ²⁶CN⁻, ²⁷CN⁻ or ²⁸Si⁻, ²⁹Si⁻, ³⁰Si⁻ isotopes simultaneously. Above
333 mass 30 it is not possible to analyse one mass intervals between the detectors; for
334 example, ³¹P⁻ and ³²S⁻ cannot be analysed simultaneously. In addition, the radius of
335 secondary ion trajectories (R) is only a window in the mass range, and the size of the
336 window is dependent on the magnetic field. For example, when the magnetic field is
337 set to look at mass ¹H on Detector 1 then the maximum mass to be simultaneously
338 analysed on Detector 5 is mass 11; therefore it is not possible to look at H and C
339 simultaneously.

340 *4.3. Mass resolution and isobaric interference*

341 The main advantage of NanoSIMS over other SIMS ion microprobes is the ability to
342 operate at high mass resolution, whilst maintaining both excellent signal transmission
343 and high spatial resolution. Analysis conditions have to be optimised to obtain
344 satisfactory separation of isobars (i.e. other isotopes and molecular complexes with
345 the similar mass) that may interfere with the ion species of interest. For example, C
346 isotope measurements require a mass resolving power of ~3000 to separate the ¹³C⁻
347 peak from the overlapping ¹²C¹H⁻ peak. Similarly, a mass resolving power of ~7200 is
348 necessary to separate ¹³C₂⁻ from ¹²C¹⁴N⁻ on mass 26 (Clode et al., 2007). This high

349 mass resolution is achieved through the use of slits at the entrance to the mass
350 spectrometer. The geometry of the NanoSIMS, however, minimises the loss of signal
351 at the slits, thus maintaining high transmission, and therefore sensitivity. In addition,
352 Cliff et al. (2002) reported isobaric interference of $^{27}\text{Al}^-$ with $^{13}\text{C}^{14}\text{N}^-$ and $^{12}\text{C}^{15}\text{N}^-$
353 when analysing soil using a Ga^+ primary ion probe with TOF-SIMS. Such
354 interferences are not an issue in NanoSIMS analysis as $^{27}\text{Al}^-$ ions do not ionise very
355 easily in the negative polarity (i.e. using a Cs^+ primary ion beam), thus the yield of
356 secondary Al^- is very low and interferences with CN^- ions are negligible.

357 *4.4. Quantitative analysis of isotopes*

358 Quantitative SIMS analysis is difficult because although the secondary ion intensity of
359 a particular element is proportional to the concentration of the element in the sample
360 the proportionality factors are not readily obtained (Morrison et al., 1994). The latter
361 include the practical ion yield and the total sputtering yield. These vary with variation
362 in the matrix of the sample. Matrix effects in resin-embedded tissue (Brenna and
363 Morrison, 1986) and freeze-dried cells (Chandra et al., 1987) appear to be small or
364 negligible. This means that relative ion intensities from compartments in the same
365 sample can be obtained by normalising to an ion such as ^{12}C that is representative of
366 the total mass of the analysed compartment. Matrix effects, however, have not been
367 checked to determine the inhomogeneity that can now be resolved at the μm scale
368 using NanoSIMS. The most promising approach is based on the use of matching
369 standards in which the analyte of interest is dispersed in a matrix mimicking the
370 composition of the sample matrix. However, when working with soils containing a
371 diverse mixture of micro-organisms within a heterogeneous soil matrix that is
372 embedded in resin or sulphur, the preparation of representative standards becomes
373 challenging. Nevertheless, isotopic ratios can be readily obtained, providing a semi-

374 quantitative analysis of the isotopes of interest, independent of matrix effects and
375 variations in topography etc. From this, levels of isotopic enrichment in comparison to
376 natural terrestrial values can be accurately measured and statistically analysed.

377 *4.5. General practical considerations*

378 The effective working field of view of the NanoSIMS instrument is necessarily
379 restricted (usually 30-50 μm field of view). For example, in the study by Herrmann et
380 al. (2007), the maximum workable field of view per ion image was approximately 30
381 x 30 μm^2 since beyond this there was notable distortion at the edges. A challenge
382 arising from this constraint is that methods have to be devised for establishing the
383 precise location to which to apply NanoSIMS in probing the sample. This can be
384 achieved using microscopic visualisation at increasing resolution, but only if features
385 being visualised by such microscopy are pertinent to locating regions-of-interest for
386 NanoSIMS probing. This is particularly challenging at the very small spatial scales
387 involved with nano-scale locations. The NanoSIMS has an optical microscope
388 connected to a CCD camera, and a secondary electron detector (only available with
389 Cs^+ primary beam) which assist in navigation (Table 1). Existing methods such as
390 digital image analysis, transmission and scanning electron microscopy have been used
391 to characterise samples in more detail and to identify potentially suitable areas for
392 NanoSIMS analysis (Figure 6 and Herrmann et al., 2007). The cost and limitations of
393 analysis of samples by NanoSIMS mean that the targeting of samples for NanoSIMS
394 analysis needs to be carried out with great care across a range of scales e.g. the
395 selection of sample sites and experimental treatments as well as identification of the
396 most appropriate field of view. Thus, it is clear that the value of NanoSIMS is as a
397 component of larger-scale integrated studies where a range of methods are combined
398 (Guerquin-Kern et al., 2005).

399 There is however a severe constraint to the realisation of such goals, that is essentially
400 scale-related. Location and visualisation of cells where the majority of such cells are
401 duly labelled is relatively straightforward – hence the success of *in situ* mapping of
402 bacteria and fungi using universal stains (Nunan et al., 2001; 2003, Harris et al.,
403 2003), and the proof-of-concept study by Herrmann et al. (2007) where all bacteria
404 were guaranteed to be labelled with ^{15}N . However, where specific labels are used, by
405 definition only a subset of the total population will be labelled (and therefore
406 potentially visualisable) there is soon an issue of locating cells within the areas
407 defined by microscopic fields of view. For example, consider if 1% of the soil
408 bacterial community were labelled, which would be an upper bound for even a
409 relatively common property associated with soil micro-organisms such as
410 nitrification. The frequency of occurrence of labelled cells, even if the property were
411 evenly distributed throughout the community, would then be such that a very large
412 number of fields of view would not contain a single instance of labelled cells. If the
413 organisms were spatially aggregated, the problem would be exacerbated. These issues
414 are related to the proportion of cells likely to be labelled, and hence the rarity of the
415 prescribed organismal group or function. Techniques will therefore need to be
416 developed to allow rapid screening of samples to determine their likelihood of
417 containing target material.

418 **5. Potential applications of NanoSIMS within the field of biogeochemistry and** 419 **soil ecology**

420 In the previous sections, we have highlighted the potential of NanoSIMS but also the
421 challenges of the application of this method. The sample preparation methods prior to
422 NanoSIMS analysis (described above), mean that the study of soluble soil

423 components not stabilised by fixation is not possible. Consequently, the technique is
424 likely to be most suited to studying assimilatory rather than dissimilatory processes,
425 the functional consequences of the spatial organisation of microbial activity and how
426 these are affected by interactions with the local physical habitat (aggregate structure,
427 mineralogical associations), with other micro-organisms (horizontal gene transfer,
428 food web relations, inter-hyphal interactions) or environmental factors such as
429 moisture content and temperature. In the following sections we discuss the current
430 state-of-the-art in some of these areas and identify the areas in which integrated
431 experiments including NanoSIMS analysis might be of significant benefit.

432 *5.1. Biogeochemistry*

433 5.1.1 Phosphatic fertiliser and organic amendments

434 The fixation of phosphatic fertiliser at soil mineral surfaces has long been known as a
435 phenomenon, but the identification and spatial location of such fixation sites remains
436 elusive. The role of soil organic matter and microbial activity in these processes is
437 also recognised and has increasingly been elucidated. A variety of mechanisms has
438 been proposed whereby increased soil organic matter and/or microbial activity
439 reduces sorption of added P (Ayaga et al., 2005; Guppy et al., 2005). Use of organic
440 amendments may reduce P sorption or simply increase P inputs (Iyamuremye and
441 Dick, 1996; Haynes and Mokolobate, 2001). However, the precise mechanisms and
442 reactions at soil surfaces and their controls are not well understood. NanoSIMS may
443 offer an opportunity to visualise the soil surface:P interactions in new ways and
444 together with radio-isotopic studies of P dynamics in soil may allow the controls over
445 sorption reactions to be determined.

446 5.1.2. Stabilisation of soil organic matter

447 The mechanisms by which organic matter is stabilised in soils are still poorly
448 understood, and it is notable that some postulated mechanisms are currently only
449 weakly supported by data (von Lützow et al., 2006). Recently, Kleber et al. (2007)
450 presented a new conceptual model of the multi-layered structure of organo-mineral
451 associations in soils suggesting that organic matter sorbs to mineral surfaces in a
452 discrete zonal sequence (contact, hydrophobic and kinetic zones). This new model
453 sharply contrasts with the existing paradigm of organo-mineral interactions
454 (Stevenson et al., 1985) which were visualised as associations of large,
455 multifunctional polymers with mineral surfaces via a broad range of bonding
456 mechanisms (Stevenson, 1985; Leinweber and Schulten, 1998). The new conceptual
457 model (Kleber et al., 2007) has been derived from blending an earlier concept of
458 Wershaw (1993) with recent published evidence from empirical studies of organo-
459 mineral interfaces. There is certainly a need to experimentally validate this model.
460 NanoSIMS with its ability to simultaneously detect up to five ion species with high
461 sensitivity from the same micro-volume should allow the study of soil organic matter
462 stabilisation mechanisms (i.e. organic matter interactions with the soil matrix) as
463 never before.

464 Physically uncomplexed organic matter (isolated on the basis of particle size or by
465 density fractionation techniques) has an important role in soil nutrient supply and
466 structure formation. Natural abundance studies of fractionated organic matter,
467 following the differential fractionation of ^{13}C by C4 and C3 plants, have revealed
468 much about the kinetics and turnover of physically uncomplexed organic matter in
469 soil; results that are important in the management of C sequestration (Gregorich et al.,
470 2006). However, the range of physical fractionation methods commonly used to

471 measure the pools of physically uncomplexed organic matter do not allow the
472 importance of the spatial arrangement of micro-organisms, soil organic matter and
473 primary particles to be studied since they are necessarily destructive of soil structure.
474 The potential of synchrotron-based X-ray computed tomography, near-edge X-ray
475 absorption fine structure (NEXAFS) spectroscopy, scanning transmission X-ray
476 microscopy (STXM), Fourier-transform infrared spectroscopy-attenuated total
477 reflectance (FTIR-ATR) and X-ray micro-fluorescence have all been used to map the
478 physical and chemical make-up of soil at the micro-scale (Lehmann et al., 2005;
479 Solomon et al., 2005; Nunan et al., 2006; van Oort et al., 2006). Such approaches
480 have the potential to shed light on the functional significance of interactions among
481 the various components of soil. When coupled with the targeted application of
482 NanoSIMS, this is likely to lead to increased understanding of the importance of
483 physical location and biophysical interactions as a key constraint in the turnover of
484 organic matter in soil. More proof-of-concept work is needed with NanoSIMS to
485 establish whether natural isotopic fractionation, such as occurs during the contrasting
486 routes of photosynthesis in C3 and C4 plants, can be detected. Nonetheless
487 NanoSIMS offers opportunities to add value to studies, for example such as Devevre
488 and Howarth (2001) by allowing focussed study of organo-mineral associations and
489 uncomplexed organic matter within the soil matrix following the use of isotopically-
490 enriched tracers in fertilisers or plant materials.

491 5.1.3. Spatial distribution of gross N assimilation processes within the soil matrix

492 Kirkham and Bartholomew (1954; 1955) first formulated differential equations to
493 estimate gross N processes in soils that form the basic concepts of the ^{15}N isotope
494 dilution technique. Dissimilatory processes such as gross N mineralisation and
495 nitrification processes are estimated by enriching the product pool with ^{15}N and

496 measuring the changes of the product pool size and dilution of ^{15}N in this pool over
497 time. The ^{15}N isotope dilution technique has been widely applied to the study of N
498 (Murphy et al., 2003; Booth et al., 2005) and has revealed complex interacting
499 processes at the heart of the soil N cycle (e.g. Schimel et al. 1989; Davidson et al.,
500 1992; Hart et al., 1994; Cookson et al., 2006). Gross N assimilation processes, usually
501 termed gross N immobilisation, by the microbial biomass in soil is a critical process in
502 the regulation of the soil internal N cycle (Murphy et al., 2003). However, gross N
503 immobilisation rates in soils are difficult to estimate at a meso-scale and studies are
504 fraught with difficulty. Gross N immobilisation rates are estimated indirectly by
505 measuring ^{15}N tracers into the microbial biomass using the fumigation-extraction
506 method (e.g. Ledgard et al., 1998; Hatch et al. 2000) or by determination of residual
507 ^{15}N in soils after KCl extractions in combination with numerical modelling of N
508 processes (e.g. Mary et al., 1998; Recous et al., 1999; Andersen and Jensen, 2001).
509 The ^{15}N isotope dilution approach indicates the importance of gross N immobilisation
510 process, but gives relatively little insight into the major controlling factors at micro-
511 scale as both approaches treat the microbial biomass as a black box. In addition, there
512 are several assumptions inherent in ^{15}N isotope dilution technique (Murphy et al.,
513 2003) and violation of the assumption of equilibrium and identical behaviour of added
514 and native N has been reported to significantly impact estimates of gross N
515 transformation rates (Monaghan, 1995; Watson, et al. 2000; Cliff et al., 2002; Luxhøi
516 et al., 2004; Herrmann et al., 2005).

517 Spatial distribution of gross N immobilisation processes could potentially be
518 quantified by superimposing maps derived from digital image analysis of soil thin
519 sections (i.e. distribution of both active and non-active micro-organisms; see below)
520 and NanoSIMS images examining the spatial distribution of ^{15}N immobilising micro-

521 organisms (i.e. active ^{15}N immobilising micro-organisms). Because soil thin sections
522 are often prepared on glass slides which do not allow NanoSIMS analysis due to
523 mounting issues (Section 4.1.), there is still a need to employ a method to couple
524 digital imaging of biological soil thin sections with NanoSIMS image analysis.
525 However, given the high degree of spatial resolution of NanoSIMS, this method may
526 have the potential to quantify the spatial distribution of gross N immobilisation and
527 may give new insights of the major controlling factors of this process (e.g.
528 environmental factors such as moisture content and temperature) at the micro-scale as
529 well as validating the assumption of equilibrium and identical behaviour of added and
530 native N.

531 5.2. Soil ecology

532 5.2.1. Association of micro-organisms with particular minerals within the soil matrix
533 Work by Gleeson et al. (2005; 2006) has shown particular relationships between
534 micro-organisms and minerals during weathering of exposed rock surfaces. Bacterial
535 and fungal community structure was driven by the chemical composition of the
536 mineral *in situ*. Biological breakdown of minerals has been shown to be an important
537 process during micro-scale weathering in aquatic and soil environments (Brehm et al.,
538 2005). Scanning transmission X-ray microscopy and spectromicroscopy has been
539 used at the sub 40-nm scale to study bio-weathering products following microbial
540 interaction with a Fe-Mg-orthopyroxene (Benzerara et al., 2005). It has also been
541 postulated that low pH and bacterial rich environments within the guts of worms
542 promote biological weathering; new weathering products were detected by X-ray
543 diffraction and Fourier transform infrared spectroscopy after a mineral mud was
544 ingested and excreted by worms (Needham et al., 2004; Needham et al., 2006).

545 However, these techniques have a limited elemental range. The capability of
546 NanoSIMS to measure light elements, particularly C and N and their isotopes, should
547 allow increased understanding of the microbial: mineral interactions at rock surfaces
548 and within soils.

549 5.2.2. Spatial distribution of active micro-organisms at the micro-scale

550 Determining the spatial location of particular micro-organisms within the soil matrix,
551 and especially their actual or potential functional capabilities, is a desirable goal in
552 soil ecology. There are many hypothesised reasons why the precise location of cells is
553 pertinent to soil function. For example, Grundmann and Normand (2000) found that
554 the genetic distances of the genus *Nitrobacter* at a local scale (< 3 cm) were as large
555 as those among reference strains from a range of geographical areas, suggesting that
556 the biological and physical processes regulating diversity occur at much finer scales.
557 Others have suggested that the activity of microbial cells can be affected by the
558 proximity of other active cells (Darrah et al., 1987; Strong et al., 1997), that the
559 response of microbial communities to external stresses is modulated by the micro-
560 scale location (Ranjard et al., 2000a) and that the spatial spread of cells has an impact
561 on overall activity (Pallud et al., 2004).

562 Two methodological approaches have been developed for the quantification of spatial
563 patterns of micro-organisms at the micro-scale and their impact on microbial function.
564 The methods have inherent weaknesses most of which may be overcome with
565 NanoSIMS. The first method is a micro-sampling technique of specific active
566 microbial groups and it is based on the relation between sample size and the
567 frequency of occurrence of a process (Grundmann et al., 2001; Dechesne et al., 2003).
568 The advantage of this approach is that the three-dimensional spatial distribution of
569 bacterial activity and their functional significance can be studied but it is not possible

570 to quantify the spatial relationship between micro-organisms and soil structure. The
571 second is the use of universal fluorescent staining of soil bacteria combined with
572 preparation of biological soil thin sections to examine *in situ* spatial distribution of
573 micro-organisms at the micro-scale (White et al., 1994; Fisk et al., 1999; Nunan et al.
574 2001; Li et al., 2004). Digital image analysis of soil thin sections allows the
575 relationship between micro-organisms and the microbial habitat to be quantified but
576 does not distinguish between active and non-active micro-organisms and patterns are
577 measured in two dimensions. Consequently, the functional significance of a given
578 distribution is difficult to ascertain, specific functions cannot be attributed to bacteria
579 and a degree of extrapolation is necessary in order to account for three dimensions.

580 A comprehensive range of nucleic-acid based probes that enable the specific labelling
581 of organisms on a taxonomic or functional basis are now available (For reviews, see
582 van Elsas et al., 1998; Torsvik and Øvreås, 2002). These can be used to label
583 individual cells, and with appropriate epitopes attached, used to visualise the location
584 of such probes and the associated organisms. Fluorescently-labelled probes have wide
585 application in visualising cells using epi-fluorescence and confocal microscopy and
586 have been applied in environmental contexts, predominantly where cell
587 concentrations are relatively high and background matrices not overtly complex, such
588 as in biofilms (Neu et al., 2004) or rhizoplanes (Mogge et al., 2000; Eller et al., 2001).
589 The complex nature of soil matrices, resulting in non-specific binding of probes to
590 organic matter and the inaccessibility of target organisms to the probes means that
591 there is a significant risk of introducing spatial bias during labelling. This
592 consideration has effectively curtailed application of such probes to soil systems.
593 Whilst labelling cells with stable isotope probes may also result in spatial biases as

594 not all micro-organisms that have the capacity to use the substrate may be labelled,
595 these are likely to be more accurate.

596 5.2.3. Horizontal gene transfer

597 There is a growing body of evidence to suggest that horizontal gene transfer has
598 played an important role in shaping the evolution of bacterial communities and that it
599 is an important mechanism in soil bacterial communities' capacity to adapt to external
600 change (van Elsas and Bailey, 2002; Crawford et al., 2005). Although gene transfer
601 has been detected in soil and in other environmental samples, the controls and triggers
602 that operate *in situ* are still poorly understood (van Elsas and Bailey, 2002; Sørensen
603 et al., 2005). The frequency of transfer of mobile genetic elements from donor to
604 recipient cells occurs more readily in zones of high microbial density and metabolic
605 activity such as the rhizosphere. The frequency is known to be affected by a range of
606 factors such as soil type, moisture content, pH and temperature, though it has been
607 postulated that this may be more to do with indirect effects on population density than
608 on the frequency of transfer itself (Sørensen et al., 2005). The physiological status of
609 donor and recipient cells and their ability to sense signal molecules may also be
610 important determinants in the frequency of transfer (van Elsas and Bailey, 2002). In
611 soil the impact of many of these factors is regulated by the nature of the micro-habitat
612 in which the cells exist. By allowing the spread of an introduced trait such as the
613 capacity to degrade an enriched organic molecule to be followed at the scale of
614 individual cells, NanoSIMS provides us with the opportunity to investigate the micro-
615 conditions that are conducive to horizontal gene transfer.

616 5.2.4. Fungi

617 Filamentous (eucarpic) fungi play many significant roles in mediating transport
618 phenomena in soils, principally by virtue of the manner in which the fungal mycelium
619 is a spatially-integrating structure (Ritz, 2006). Elements and compounds are
620 mobilised within regions of the mycelial front and transported to distal regions,
621 governed by source:sink relationships largely established by the spatial organisation
622 of the mycelium in relation to the location of substrate resources and reproductive
623 structures. As well as a huge range of saprophytic contexts, two out of three of all
624 plant species (Trappe, 1987) are associated with arbuscular mycorrhizal fungi (AM
625 fungi) and the extra-radical mycelia of AM fungi are powerful underground mediators
626 of nutrient assimilation and transport to plants (Leake et al., 2004). Ectomycorrhizal
627 fungi are also abundant, to the extent that the majority of roots in natural
628 environments are not roots as such, but mycorrhizas. Experiments utilising
629 isotopically labelled materials have shown the pathways and associated gene
630 expression for uptake and transformation of N (Govindarajulu et al., 2005) and non-
631 invasive techniques have been developed to study C (Tlalka et al., 2002) and P
632 (Nielsen et al., 2002) transport within hyphae and mycelia. However, few studies of
633 AM fungi and plant relationships are able to distinguish clearly between the role of
634 the root and the fungal associates in the assimilation of nutrients (e.g. Hodge et al.,
635 2001). The high spatial resolution of NanoSIMS offers many opportunities to
636 understand more precisely the transformation and uptake of elements and compounds
637 at the mycelial front (significantly at the intra-hyphal scale), and their subsequent
638 location and transport through mycelia. Very little indeed is known about the
639 fungal:soil interface at the hyphal scale, but NanoSIMS analysis has been shown to

640 putatively identify fungal hyphae (Figure 6) and therefore it may be feasible to study
641 this interface in more detail.

642 5.2.5. N₂-fixing bacteria

643 The ability to fix atmospheric dinitrogen gas (N₂) is restricted to only a few
644 prokaryotes which have an ecological advantage over other organisms that must rely
645 on fixed sources to meet their cellular N requirements. Cyanobacteria are among the
646 most abundant classes of micro-organisms and are one of the largest global
647 contributors to atmospheric nitrogen fixation. Their evolutionary success and
648 ecological importance is largely owed to their unique ability to reduce both C and N
649 in aerobic conditions. Due to the irreversible inhibition of nitrogenase by free oxygen,
650 various mechanisms of separating the oxygen producing (photosynthesis) and
651 nitrogen reducing processes have evolved. Using 99.99 atom% NaH¹³CO₃ and ¹⁵N₂ as
652 cyanobacterial substrates, Popa et al. (unpublished data) and Pett-Ridge et al.
653 (unpublished data) have demonstrated that NanoSIMS can be used to isolate regions
654 of high N₂-fixation activity, as well as storage locations, mobilisation and utilisation
655 rates of newly fixed N in these bacteria. As this work was carried out with pure
656 cultures, the challenge ahead is to repeat this type of analysis in a more complex
657 environmental matrix such as soil.

658 **6. Conclusions**

659 There are still many challenges for the application of NanoSIMS as a robust tool to
660 improve understanding of microbial processes in soil at a micro- and nano-metre scale
661 and inform studies of biogeochemistry and soil ecology. The method itself provides
662 two main obstacles: (i) adequate sample preparation to avoid artefacts which may
663 introduce a bias in the interpretation of NanoSIMS data and (ii) location of regions-of-

664 interest. The necessity of studies explicitly focusing on sample preparation and
665 identification of region-of interest is therefore substantiated. In addition proof-of-
666 concept for many of the areas of study discussed above is still necessary. Currently
667 only *ex situ* labelled materials have been detected in the soil matrix using NanoSIMS
668 – and in that instance the soil matrix used was relatively simple, being dominated by
669 quartz sand. The application of NanoSIMS to studies within soil is still at a very early
670 stage of development. Nonetheless, NanoSIMS provides one of the only current
671 opportunities to study soil at levels of resolution and characteristic scales appropriate
672 to the operational scale for micro-organisms. Where the method is applied within
673 integrated studies and with appropriate care taken to ensure robust and relevant data
674 collection, then we believe that NanoSIMS will allow access to minute universe
675 which has previously eluded study, and interactions therein which may have profound
676 implications for understanding soil processes at field, catchment and regional scales.

677 **Acknowledgments**

678 Thanks are extended to participants of the workshop entitled ‘NanoSIMS – A
679 powerful tool for integrating the physical, chemical and biological interface in soil’
680 held at the Institute for Research on Environment and Sustainability (Newcastle
681 University, United Kingdom) for their contribution to the discussion. We thank the
682 European Commission (Marie Curie Outgoing International Fellowship Scheme FP6)
683 for financial support of Dr Anke M. Herrmann. Research described in this paper was
684 carried out using facilities at the Centre for Microscopy and Microanalysis (CMM),
685 The University of Western Australia, and at the Lawrence Livermore National
686 Laboratory (LLNL), USA. The authors wish to thank Drs Ian R. Fletcher and Peter K.
687 Weber for carrying out the NanoSIMS analysis. The CMM facility is supported by

688 University, State and Federal Government funding with the Cameca NanoSIMS50
689 funded by a Major National Research Facility (MNRF) grant through the
690 Nanostructural Analysis Network Organisation (NANO). The LLNL NanoSIMS
691 facility was initiated via a grant from the US Department of Energy's Office of
692 Science. Work in this facility was performed under the auspices of the U.S.
693 Department of Energy by the University of California, Lawrence Livermore National
694 Laboratory under Contract No. W-7405-Eng-48.

695 **References**

- 696 Adams, F., Van Vaeck, L., Barrett, R., 2005. Advanced analytical techniques:
697 platform for nano materials science. *Spectrochimica Acta Part B* 60, 13-26.
- 698 Andersen, M.K., Jensen, L.S., 2001. Low soil temperature effects on short-term gross
699 N mineralisation-immobilisation turnover after incorporation of a green manure.
700 *Soil Biology & Biochemistry* 33, 511-521.
- 701 Andrén, O., Brussaard, L., Clarholm, M., 1999. Soil organism influence on
702 ecosystem-level processes bypassing the ecological hierarchy? *Applied Soil*
703 *Ecology* 11, 177-188.
- 704 Ayaga, G., Todd, A., Brookes, P.C., 2005. Enhanced biological cycling of phosphorus
705 increases its availability to crops in low-input sub-Saharan farming systems. *Soil*
706 *Biology & Biochemistry* 38, 81-90.
- 707 Bengtsson, G., Bengtson, P., Mansson, K.F., 2003. Gross nitrogen mineralization-,
708 immobilization-, and nitrification rates as a function of soil C/N ratio and
709 microbial activity. *Soil Biology & Biochemistry* 35, 143-154.

710 Benzerara, K., Yoon, T.H., Menguy, N., Guyot, F., Tyliczszak, T., Brown, G.E.,
711 2005. Nanoscale environments associated with bioweathering of a Mg-Fe-
712 pyroxene. Proceedings of the National Academy of Sciences of the United States
713 of America 102, 979-982.

714 Bird, J.A., Torn, M.S. 2006. Fine roots vs. needles: a comparison of ^{13}C and ^{15}N
715 dynamics in a ponderosa pine forest soil. Biogeochemistry 79, 361–382.

716 Booth, M.S., Stark, J.M., Rastetter, E., 2005. Controls on nitrogen cycling in
717 terrestrial ecosystems: A synthetic analysis of literature data. Ecological
718 Monographs 75, 139-157.

719 Bradforth, S.E., Kim, E.H., Arnold, D.W., Neumark, D.M., 1993. Photoelectron
720 spectroscopy of CN-, NCO-, and NCS-. Journal of Chemical Physics 98, 800-
721 810.

722 Bradley, J.P., Keller, L.P., Thomas, K.L., Van der Wood, T.B., Brownlee, D.E., 1993.
723 Carbon analyses of IDPs sectioned in sulfur and supported on beryllium grids.
724 Lunar Planet Science 24, 173-174.

725 Bradley, J., Dai, Z.R., Erni, R., Browning, N., Graham, G., Weber, P., Smith, J.,
726 Hutcheon, I., Ishii, H., Bajt, S., Floss, C., Stadermann, F., Sandfords, S., 2005.
727 An astronomical 2175 Å feature in interplanetary dust particles. Science 307,
728 244-247.

729 Brehm, U., Gorbushina, A., Mottershead, D., 2005. The role of microorganisms and
730 biofilms in the breakdown and dissolution of quartz and glass. Palaeogeography,
731 palaeoclimatology, palaeoecology. 219, 117-129.

732 Brenna, J.T., Morrison, G.H., 1986. Ionization probability variations due to matrix in
733 ion microscopic analysis of plastic-embedded and ashed biological specimens.
734 *Analytical Chemistry* 58, 1675-1680.

735 Bruneau, P.M.C., Davidson, D.A., Grieve, I.C., Young, I.M., Nunan, N., 2005. The
736 effects of soil horizons and faunal excrement on bacterial distribution in an
737 upland grassland soil. *FEMS Microbiology Ecology* 52,139-144.

738 Castaing, R., Slodzian, G., 1962. Microanalyse par émission ionique secondaire.
739 *Journal de Microscopie* 1, 395–410.

740 Chandra, S., Ausserer, W.A., Morrison, G.H., 1987. Evaluation of matrix effects in
741 ion microscopic analysis of freeze-fractured, freeze-dried cultured cells. *Journal*
742 *of Microscopy-Oxford*. 148:223-239.

743 Chandra S., Sod, E.W., Ausserer, W.A., Morrison, G.H., 1992. Preparation of
744 biological samples for ion microscopy. *Pure and Applied Chemistry*. 64, 254-
745 262.

746 Cliff, J.B., Gaspar, D.J., Bottomley, P.J., Myrold, D.D., 2002a. Exploration of
747 inorganic C and N assimilation by soil microbes with Time-of-Flight Secondary
748 Ion Mass Spectrometry. *Applied and Environmental Microbiology* 68, 4067-
749 4073.

750 Cliff, J.B., Bottomley, P.J., Haggerty, R., Myrold, D.D., 2002b. Modeling the effects
751 of diffusion limitations on nitrogen-15 isotope dilution experiments with soil
752 aggregates. *Soil Science Society of America Journal* 66, 1868-1877.

753 Clode, P.L., Stern, R.A., Marshall, A.T., 2007. Subcellular imaging of isotopically
754 labeled carbon compounds in a biological sample by ion microprobe
755 (NanoSIMS). *Microscopy Research and Technology*. *In press*.

756 Chenu, C., Hassink, J., Bloem, J., 2001. Short-term changes in the spatial distribution
757 of microorganisms in soil aggregates as affected by glucose addition. *Biology*
758 and *Fertility of Soils* 34, 349-356.

759 Chenu, C., Tessier, D., 1995. Low temperature scanning electron microscopy of clay
760 and organic constituents and their relevance to soil microstructures. *Scanning*
761 *Microscopy* 9, 989-1010.

762 Chenu, C., Plante, A.F., 2006. Clay-sized organo-mineral complexes in a cultivation
763 chronosequence: revisiting the concept of the 'primary organo-mineral complex'.
764 *European Journal of Soil Science* 57, 596-607.

765 Cookson, W.R., Müller, C., O'Brien, P.A., Murphy, D.V., Grierson, P.F. 2006.
766 Nitrogen dynamics in an Australian semiarid grassland soil. *Ecology* 87, 2047-
767 2057.

768 Crawford, J.W., Harris, J.A., Ritz, K., Young, I.M., 2005. Towards an evolutionary
769 ecology of life in soil. *Trends in Ecology & Evolution* 20, 81-87.

770 Darrah, P.R., White, R.E., Nye, P.H., 1987. A Theoretical Consideration of the
771 Implications of Cell Clustering for the Prediction of Nitrification in Soil. *Plant*
772 and *Soil* 99, 387-400.

773 Davidson, E.A., Stark, J.M., Firestone, M.K., 1992. Internal cycling of nitrate in soils
774 of a mature coniferous forest. *Ecology* 73, 1148-1156.

775 Dechesne, A., Pallu, C., Debouzie, D., Flandrois, J.P., Vogel, T.M., Gaudet, J.P.,
776 Grundmann, G.L., 2003. A novel method for characterizing the microscale 3D
777 spatial distribution of bacteria in soil. *Soil Biology & Biochemistry* 35, 1537-
778 1546.

779 De Gryze, S., Jassogne, L., Six, J., Bossuyt, H., Wevers, M., Merckx, R., 2006. Pore
780 structure changes during decomposition of fresh residue: X-ray tomography
781 analyses. *Geoderma* 134, 82-96.

782 Devevre, O.C., Horwath, W.R., 2001. Stabilization of fertilizer nitrogen-15 into
783 humic substances in aerobic vs. waterlogged soil following straw incorporation
784 *Soil Science Society of America Journal* 65, 499-510

785 Echlin, P., 1992. *Low Temperature Microscopy and Analysis*, Plenum Press: New
786 York.

787 Eller, G., Stubner, S., Frenzel, P., 2001. Group-specific 16S rRNA targeted probes for
788 the detection of type I and type II methanotrophs by fluorescence in situ
789 hybridisation. *FEMS Microbiology Letters* 198, 91-97

790 Ettema, C.H., Wardle, D.A., 2002. Spatial soil ecology. *Trends in Ecology &*
791 *Evolution* 17, 177-183.

792 Feeney, D.S., Crawford, J.W., Daniell, T., Hallett, P.D., Nunan, N., Ritz, K., Rivers,
793 M., Young, I.M. 2006. Three-dimensional microorganization of the soil-root-
794 microbe system. *Microbial Ecology* 52, 151-158.

795 Fisk, A.C., Murphy, S.L., Tate, R.L., 1999. Microscopic observations of bacterial
796 sorption in soil cores. *Biology and Fertility of Soils* 28, 111-116.

797 Floss, C. Stadermann, F.J., Bradley, J., Dai, Z.R., Bajt, S., Graham, G., 2004. Carbon
798 and nitrogen isotopic anomalies in an anhydrous interplanetary dust particle.
799 *Science* 303, 1355-1358.

800 Floss, C., Stadermann, F.J., Bradley, J.P., Dai, Z.R., Bajt, S., Graham, G., Lea, A.S.,
801 2006. Identification of isotopically primitive interplanetary dust particles: A

802 NanoSIMS isotopic imaging study. *Geochimica et Cosmochimica Acta* 70, 2371-
803 2399.

804 Foster, R., Rovira, A., 1973. The rhizosphere of wheat roots studied by electron
805 microscopy of ultra-thin sections. "Modern Methods in the Study of Microbial
806 Ecology". *Bulletins from the Ecological Research Committee, Sweden* 17, 93-95.

807 Foster, R., Martin, J., 1981. In situ analysis of soil components of biological origin.
808 *Soil biochemistry* 5, 75-111.

809 Foster, R., Rovira, A., Cock, T. 1983. Ultrastructure of the root-soil interface.
810 *American Phytopathological Society, St Paul, Minnesota, USA.*

811 Gleeson, D.B., Clipson, N., Melville, K., Gadd, G.M., McDermott, F.P., 2005.
812 Characterization of fungal community structure on a weathered pegmatitic
813 granite. *Microbial Ecology*, 50, 360-368.

814 Gleeson, D.B., Kennedy, N.M., Clipson, N., Melville, K., Gadd, G.M., McDermott,
815 F.P., 2006. Characterization of bacterial community structure on a weathered
816 pegmatitic granite. *Microbial Ecology* 51, 526-534.

817 Govindarajulu, M., Pfeffer, P.E., Jin, H.R., Abubaker, J., Douds, D.D., Allen, J.W.,
818 Bucking, H., Lammers, P.J., Shachar-Hill, Y., 2005. Nitrogen transfer in the
819 arbuscular mycorrhizal symbiosis. *Nature* 435, 819-823.

820 Gregorich, E.G., Beare, M.H., McKim, U.F., Skjemstad, J.O., 2006. Chemical and
821 Biological Characteristics of Physically Uncomplexed Organic Matter. *Soil
822 Science Society of America Journal* 70, 975–985.

823 Grundmann, G.L., Normand, P., 2000. Microscale diversity of the genus *Nitrobacter*
824 in soil on the basis of analysis of genes encoding rRNA. *Applied and
825 Environmental Microbiology* 66, 4543-4546.

826 Grundmann, G.L., Dechesne, A., Bartoli, F., Flandrois, J.P., Chasse, J.L., Kizungu,
827 R., 2001. Spatial modeling of nitrifier microhabitats in soil. *Soil Science Society*
828 *of America Journal* 65, 1709-1716.

829 Grovenor, C.R.M, Smart, K.E., Kilburn, M.R., Shore, B., Dilworth, J.R., Martin, B.,
830 Hawes, C., Rickaby, R.E.M., 2006. Specimen preparation for NanoSIMS
831 analysis of biological materials. *Applied Surface Science* 252, 6917–6924.

832 Guerquin-Kern, J.-L., Hillion, F., Madelmont, J.-C., Labarre, P., Papon, J., Croisy, A.,
833 2004. Ultra-structural cell distribution of the melanoma marker iodobenzamide:
834 improved potentiality of SIMS imaging in life sciences. *BioMedical Engineering*
835 *OnLine* 3(10), 1-7.

836 Guerquin-Kern, J.-L., Wu, T.-D. Quintana, C. Croisy, A., 2005. Progress in analytical
837 imaging of the cell by dynamic secondary ion mass spectrometry (SIMS
838 microscopy). *Biochimica et Biophysica Acta* 1724, 228-238.

839 Guppy, C.N., Menzies, N.W., Moody, P.W., Blamey, F.P.C., 2005. Competitive
840 sorption reactions between phosphorus and organic matter in soil: a review.
841 *Australian Journal of Soil Research* 43, 189-202.

842 Hallegot, P., Peteranderl, R., Lechene, C. J., 2004. In-situ imaging mass spectrometry
843 analysis of melanin granules in the human hair shaft. *Journal of Investigative*
844 *Dermatology* 122, 381-386.

845 Harris, P.J., 1994. Consequences of the spatial distribution of microbial communities
846 in soil. In: Ritz, K., Dighton, J., Giller, K.E. (Eds.), *Beyond the biomass:*
847 *Compositional and functional analysis of soil microbial communities.* John
848 Wiley, Chichester, U.K., pp. 239-246.

- 849 Harris, K., Young, I.M., Gilligan, C.A., Otten, W., Ritz, K., 2003. Effect of bulk
850 density on the spatial organisation of the fungus *Rhizoctonia solani* in soil.
851 FEMS Microbiology Ecology 44, 45-56
- 852 Hart, S.C., Nason, G.E., Myrold D.D., Perry, D.A., 1994. Dynamic of gross nitrogen
853 transformations in an old-growth forest – The carbon connection. Ecology 75,
854 880-891.
- 855 Hatch, D.J., Jarvis, S.C., Parkinson, R.J. Lovell, R.D., 2000. Combining field
856 incubation with ¹⁵N labelling to examine N transformations in low to high
857 intensity grassland management systems. Biology and Fertility of Soils 30, 492-
858 499.
- 859 Haynes, R.J., Mokolobate, M.S., 2001. Amelioration of Al toxicity and P deficiency
860 in acid soils by additions of organic residues: a critical review of the phenomenon
861 and the mechanisms involved. Nutrient Cycling in Agroecosystems 59, 47-63.
- 862 Hellebrand, E., Snow, J.E., Mostefaoui, S., Hoppe, P., 2005. Trace element
863 distribution between orthopyroxene and clinopyroxine in peridotites from the
864 Gakkal Ridge: a SIMS and NanoSIMS study. Contributions to Mineralogy and
865 Petrology 150, 486-504.
- 866 Herrmann, A., Witter, E., Kätterer, T., 2004. Can N mineralisation be predicted from
867 soil organic matter? Carbon and gross N mineralisation rates as affected by long-
868 term additions of different organic amendments. In: Hatch, D.J., Chadwick, D.R.,
869 Jarvis, S.C., Roker, J.A., (Eds.), Controlling nitrogen flows and losses.
870 Wageningen Academic Publishers, pp. 113-121.

871 Herrmann, A., Witter, E., Kätterer, T., 2005. A method to assess whether ‘preferential
872 use’ occurs after ^{15}N ammonium addition; implication for the ^{15}N isotope dilution
873 technique. *Soil Biology & Biochemistry* 37, 183–186.

874 Herrmann, A.M., Clode, P.L., Fletcher, I.R., Nunan, N., Stockdale, E.A., O’Donnell,
875 A.G., Murphy D.V., 2007. A novel method for the study of the biophysical
876 interface in soils using Nano-Scale Secondary Ion Mass Spectrometry. *Rapid*
877 *Communications in Mass Spectrometry*, *Accepted for publication*.

878 Hodge, A., Campbell, C.D., Fitter, A.H., 2001. An arbuscular mycorrhizal fungus
879 accelerates decomposition and acquires nitrogen directly from organic material.
880 *Nature* 413, 297-299.

881 Hoppe, P., Ott, U., Lugmair, G.W., 2004. NanoSIMS, the new tool of choice: ^{26}Al ,
882 ^{44}Ti , ^{49}V , ^{53}Mn , ^{60}Fe , and more. *New Astronomy Reviews* 48, 171-176.

883 Hoppe, P. 2006. NanoSIMS: A new tool in cosmochemistry. *Applied Surface Science*
884 252, 7102-7106.

885 Iyamuremye, F., Dick, R.P., 1996. Organic amendments and phosphorus sorption by
886 soils. *Advances in Agronomy* 56, 139-185.

887 Kailas, L., Audinot, J.N., Migeon, H.N., Bertrand, P., 2005. Multitechnique
888 characterization of thin films of immiscible polymer systems: PS-b-PMMA
889 diblock copolymers and PS-PMMA symmetric blends. *Surface and Interface*
890 *Analysis* 37, 435-443.

891 Kailas, L., Audinot, J.N., Migeon, H.N., Bertrand, P., 2006. Surface segregational
892 behaviour studied as an effect of thickness by SIMS and AFM in annealed PS-
893 PMMA blend and block copolymer thin films. *Composite Interfaces* 13, 423-439.

894 Kilbertus, G., 1980. Study of microhabitats in soil aggregates – relation to bacterial
895 biomass and size of prokaryotes. *Revue d'écologie et de biologie du sol* 17, 543-
896 557.

897 Kirkham, D., Bartholomew, W.V., 1954. Equations for following nutrient
898 transformations in soil, utilizing tracer data. *Soil Science Society of America*
899 *Proceedings* 18, 33–34.

900 Kirkham, D., Bartholomew, W.V., 1955. Equations for following nutrient
901 transformations in soil, utilizing tracer data: II. *Soil Science Society of America*
902 *Proceedings* 19, 189–192.

903 Kleber, M., Sollins, P., Sutton, R., 2007. A conceptual model of organo-mineral
904 interactions in soils: Self-assembly of organic molecular fragments into
905 multilayered structures on mineral surfaces. *Biogeochemistry*. *Accepted for*
906 *publication*.

907 Kleinfeld, A.M., Kampf, J.P., Lechene, C. J., 2004. Transport of C-13-oleate in
908 adipocytes measured using multi imaging mass Spectrometry. *Journal of the*
909 *American Society for Mass Spectrometry* 15, 1572-1580.

910 Kraft, M.L., Weber, P.K., Longo, M.L., Hutcheon, I.D., Boxer, S.G., 2006. Phase
911 separation of lipid membranes analyzed with high-resolution secondary ion mass
912 spectrometry. *Science* 313, 1948-1951.

913 Kubiena, W.L., 1938. *Micropedology*. Collegiate Press, INC. Ames, Iowa, USA.

914 Labotka, T.C., Cole, D.R., Fayek, M., Riciputi, L.R., Stadermann, F.J., 2004. Coupled
915 cation and oxygen-isotope exchange between alkali feldspar and aqueous
916 chloride solution. *American Mineralogist* 89, 1822-1825.

- 917 Ledgard, S.F., Jarvis, S.C., Hatch, D.J., 1998. Short-term nitrogen fluxes in grassland
918 soils under different long-term nitrogen managements regimes. *Soil Biology &*
919 *Biochemistry* 30, 1233-1241.
- 920 Leake , J. R., Johnson, D., Donnelly, D. P., Muckle, G. E., Boddy, L., Read, D. J.,
921 2004. Networks of power and influence: the role of mycorrhizal mycelium in
922 controlling plant communities and agroecosystem functioning. *Canadian Journal*
923 *of Botany* 82, 1016-1045.
- 924 Lehmann, J., Liang, B.Q., Solomon, D., Lerotic, M., Luizão, F., Kinyangi, J. Schäfer,
925 T., Wirick, S., Jacobsen C., 2005. Near-edge X-ray absorption fine structure
926 (NEXAFS) spectroscopy for mapping nano-scale distribution of organic carbon
927 forms in soil: Application to black carbon particles. *Global Biogeochemical*
928 *Cycles* 19, Art. No. GB1013.
- 929 Leinweber, P., Schulten, H.-R., 1998. Advances in analytical pyrolysis of soil organic
930 matter. *Journal of Analytical and Applied Pyrolysis* 47, 165-189.
- 931 Li , Y., Dick, W.A., Tuovinen, O.H., 2004. Fluorescence microscopy for visualization
932 of soil microorganisms - a review. *Biology and Fertility of Soils* 39, 301-311.
- 933 Long, T., Or, D., 2005. Aquatic habitats and diffusion constraints affecting microbial
934 coexistence in unsaturated porous media. *Water Resources Research* 41.
- 935 Luxhøi, J., Nielsen N.E., Jensen L.S., 2004. Effect of soil heterogeneity on gross
936 nitrogen mineralization measured by ¹⁵N-pool dilution techniques. *Plant and Soil*
937 262, 263-275.
- 938 Mary, B., Recous, S., Robin, D., 1998. A model for calculating nitrogen fluxes in soil
939 using ¹⁵N tracing. *Soil Biology & Biochemistry* 30, 1963-1979.

940 Meibom A., Cuif, J.-P., Hillion, F., Constantz, B.R., Juillet-Leclerc, A., Dauphin, Y.,
941 Watanabe, T., Dunbar, R.B., 2004. Distribution of Mg in coral skeleton.
942 Geophysical Research Letter 31, L23306.

943 Messenger, S., Keller, L.P., Stadermann, F.J., Walker, R.M., Zinner, E., 2004.
944 Samples of stars beyond the solar system: Silicate grains in interplanetary dust
945 Science 300, 105-108.

946 Mogge, B., Loferer, C., Agerer, R., Hutzler, P., Hartmann, A., 2000. Bacterial
947 community structure and colonization patterns of *Fagus sylvatica* L-
948 ectomycorrhizospheres as determined by fluorescence in situ hybridization and
949 confocal laser scanning microscopy. Mycorrhiza 9, 271-278.

950 Monaghan, R., 1995. Errors in estimates of gross rates of nitrogen mineralization due
951 to non-uniform distributions of ¹⁵N label. Soil Biology & Biochemistry 27, 855-
952 859.

953 Morrison, G.H., Gay, I., Chandra, S., 1994. Ion microscopy in biology. Scanning
954 Microscopy Supplement 8, 359-370.

955 Mummey, D.L., Stahl, P.D., 2004. Analysis of soil whole- and inner-microaggregate
956 bacterial communities. Microbial Ecology 48, 41-50.

957 Murphy, D.V., Recous, S., Stockdale, E.A., Fillery, I.R.P., Jensen, L.S., Hatch, D.J.,
958 Goulding, K.W.T., 2003. Gross nitrogen fluxes in soil: theory, measurement and
959 application of ¹⁵N pool dilution techniques. Advances in Agronomy 79, 69–118.

960 Needham, S. J., Worden, R. H., McIlroy, D., 2004. Animal-sediment interactions: the
961 effect of ingestion and excretion by worms on mineralogy. Biogeosciences 1,
962 113-121.

- 963 Needham, S. J., Worden, R. H., Cuadros, J., 2006. Sediment ingestion by worms and
964 the production of bio-clays: a study of macrobiologically enhanced weathering
965 and early diagenetic processes. *Sedimentology* 53, 567-579.
- 966 Neu, T.R., Woelfl, S., Lawrence, J.R. 2004. Three-dimensional differentiation of
967 photo-autotrophic biofilm constituents by multi-channel laser scanning
968 microscopy (single-photon and two-photon excitation). *Journal of*
969 *Microbiological Methods* 56, 161-172.
- 970 Nielsen J.S., Joner, E. J., Declerck., S., Olsson, S., Jakobsen, I., 2002. Phospho-
971 imaging as a tool for visualisation and non-invasive measurement of P transport
972 dynamics in arbuscular mycorrhizas. *New Phytologist* 154, 809-819.
- 973 Nunan, N., Ritz, K., Crabb, D., Harris, K., Wu, K.J., Crawford, J.W., Young, I.M.,
974 2001. Quantification of the in situ distribution of soil bacteria by large-scale
975 imaging of thin sections of undisturbed soil. *FEMS Microbiology Ecology* 37,
976 67-77.
- 977 Nunan, N., Wu, K.J., Young, I.M., Crawford, J.W., Ritz, K., 2003. Spatial distribution
978 of bacterial communities and their relationships with the micro-architecture of
979 soil. *FEMS Microbiology Ecology* 44, 203-215.
- 980 Nunan, N., Ritz, K., Rivers, M., Feeney, D.S., Young, I.M., 2006. Investigating
981 microbial micro-habitat structure using X-ray computed tomography. *Geoderma*
982 133, 398-407.
- 983 Pacholski, M.L., Winograd, N., 1999. Imaging with mass spectrometry. *Chemical*
984 *Reviews* 99, 2977-3005.
- 985 Pallud, C., Dechesne, A., Gaudet, J.P., Debouzie, D., Grundmann, G.L., 2004.
986 Modification of spatial distribution of 2,4-dichloro- phenoxyacetic acid degrader

987 microhabitats during growth in soil columns. *Applied and Environmental*
988 *Microbiology* 70, 2709-2716.

989 Peteranderl, R., Lechene, C.J., 2004. Measure of carbon and nitrogen stable isotope
990 ratios in cultured cells. *Journal of the American Society for Mass Spectrometry*
991 15, 478-485.

992 Postma, J., Altemüller, H.J., 1990. Bacteria in Thin Soil Sections Stained with the
993 Fluorescent Brightener Calcofluor White M2R. *Soil Biology & Biochemistry* 22,
994 89-96.

995 Ranjard, L., Nazaret, S., Gourbiere, F., Thioulouse, J., Linet, P., Richaume, A., 2000a.
996 A soil microscale study to reveal the heterogeneity of Hg(II) impact on
997 indigenous bacteria by quantification of adapted phenotypes and analysis of
998 community DNA fingerprints. *FEMS Microbiology Ecology* 31, 107-115.

999 Ranjard, L., Poly, F., Combrisson, J., Richaume, A., Gourbiere, F., Thioulouse, J.,
1000 Nazaret, S., 2000b. Heterogeneous cell density and genetic structure of bacterial
1001 pools associated with various soil microenvironments as determined by
1002 enumeration and DNA fingerprinting approach (RISA). *Microbial Ecology* 39,
1003 263-272

1004 Recous, S., Aita, C., Mary, B., 1999. In situ changes in gross N transformations in
1005 bare soil after addition of straw. *Soil Biology & Biochemistry* 31, 119-133.

1006 Ritz, K., 2006. Fungal roles in transport processes in soils. In: Gadd, G.M., (Ed.),
1007 *Fungi in Biogeochemical Cycles*, Cambridge University Press, pp. 51-73.

1008 Sano, Y., Shirai, K., Takahata, N., Hirata, T., Sturchio, N.C., 2005. Nano-SIMS
1009 analysis of Mg, Sr, Ba and U in natural calcium carbonate. *Analytical Sciences*
1010 21, 1091-1097.

- 1011 Schimel, J.P., Jackson, L.E., Firestone, M.K., 1989. Spatial and temporal effects on
1012 plant-microbial competition for inorganic nitrogen in a California annual
1013 grassland. *Soil Biology & Biochemistry* 21, 1059-1066.
- 1014 Sierra, J., Renault, P., Valles, V., 1995. Anaerobiosis in saturated soil aggregates:
1015 Modelling and experiment. *European Journal of Soil Science* 46, 519-531.
- 1016 Slodzian, G., Daigne, B., Girard, F., Boust, F., Hillion, F., 1992. Scanning secondary
1017 ion analytical microscopy with parallel detection. *Biology of the Cell* 74, 43-50.
- 1018 Stern, R.A., Fletcher, I.R., Rasmussen, B., McNaughton, N.J., Griffin, B.J., 2005. Ion
1019 microprobe (NanoSIMS 50) Pb-isotope geochronology at <5 µm scale.
1020 *International Journal of Mass Spectrometry* 244, 125-134.
- 1021 Solomon, D., Lehmann, J., Kinyangi, J., Liang, B.Q., Schafer, T., 2005. Carbon K-
1022 edge NEXAFS and FTIR-ATR spectroscopic investigation of organic carbon
1023 speciation in soils. *Soil Science Society of America Journal*. 69, 107-119.
- 1024 Sørensen, S.J., Bailey, M., Hansen, L.H., Kroer, N., Wuertz, S., 2005. Studying
1025 plasmid horizontal transfer in situ: A critical review. *Nature Reviews*
1026 *Microbiology* 3, 700-710.
- 1027 Stevenson, F.J., 1985. Geochemistry of soil humic substances. In: McKnight D.M.,
1028 (Ed.), *Humic Substances in Soil, Sediment and Water: Geochemistry, Isolation*
1029 *and Characterization*. John Wiley and Sons, New York.
- 1030 Strong, D.T., Sale, P.W.G., Helyar, K.R., 1997. Initial soil pH affects the pH at which
1031 nitrification ceases due to self-induced acidification of microbial microsites.
1032 *Australian Journal of Soil Research* 35, 565-570.
- 1033 Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils.
1034 *Journal of Soil Science* 33, 141-163.

- 1035 Tippkötter, R., Ritz, K., 1996. Evaluation of polyester, epoxy and acrylic resins for
1036 suitability in preparation of soil thin sections for in situ biological studies.
1037 *Geoderma* 69, 31-57.
- 1038 Tlalka, M., Watkinson, S.C., Darrah, P.R., Fricker, M.D., 2002. Continuous imaging
1039 of amino-acid translocation in intact mycelia of *Phanerochaete velutina* reveals
1040 rapid, pulsatile fluxes. *New Phytologist* 153, 173-184.
- 1041 Torsvik, V., Øvreås, L., 2002. Microbial diversity and function in soil: from genes to
1042 ecosystems. *Current Opinion in Microbiology* 5, 240-245.
- 1043 Trappe, J.M., 1987. Phylogenetic and ecologic aspects of mycotrophy in the
1044 angiosperms from an evolutionary standpoint. In: Safir, G.R., (Ed.),
1045 *Ecophysiology of VA mycorrhizal plants*. CRC Press, Inc. Boca Raton, Florida,
1046 USA, pp. 5-25.
- 1047 Treves, D.S., Xia, B., Zhou, J., Tiedje, J.M., 2003. A two-species test of the
1048 hypothesis that spatial isolation influences microbial diversity in soil. *Microbial*
1049 *Ecology* 45, 20-28.
- 1050 van Elsas, J.D., Duarte, G.F., Rosado, A.S., Smalla, K., 1998. Microbiological and
1051 molecular biological methods for monitoring microbial inoculants and their
1052 effects in the soil environment. *Journal of Microbiological Methods* 32, 133-154.
- 1053 van Elsas, J.D., Bailey, M.J., 2002. The ecology of transfer of mobile genetic
1054 elements. *FEMS Microbiology Ecology* 42, 187-197.
- 1055 van Oort, F., Jongmans, A.G., Citeau, L., Lamy, I., Chevallier, P., 2006. Microscale
1056 Zn and Pb distribution patterns in subsurface soil horizons: an indication for
1057 metal transport dynamics. *European Journal of Soil Science* 57, 154-166.

1058 von Lützow, M., Kögel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G.,
1059 Marschner, B., Flessa, H., 2006. Stabilization of organic matter in temperate
1060 soils: mechanisms and their relevance under different soil conditions - a review.
1061 European Journal of Soil Science 57, 426-445.

1062 Wardle, D.A., Giller, K.E., 1996. The quest for a contemporary ecological dimension
1063 to soil biology. Soil Biology & Biochemistry 28, 1549-1554.

1064 Watson, C.J., Travers, G., Kilpatrick, D.J., Laidlaw, A.S., O’Riordan, E., 2000.
1065 Overestimation of gross N transformation rates in grassland soils due to non-
1066 uniform exploitation of applied and native pools. Soil Biology & Biochemistry
1067 32, 2019–2030.

1068 Wershaw, R.L., 1993. Model for Humus in Soils and Sediments. Environmental
1069 Science and Technology 27, 814-816.

1070 White, D., Fitzpatrick, E.A., Killham, K., 1994. Use of stained bacterial inocula to
1071 assess spatial-distribution after introduction into soil. Geoderma 63, 245-254.

1072 Wu, K.J., Nunan, N., Crawford, J.W., Young, I.M., Ritz, K., 2004. An efficient
1073 Markov chain model for the simulation of heterogeneous soil structure. Soil
1074 Science Society of America Journal 68, 346-351.

1075 Young, I.M., Ritz, K., 1998. Can there be a contemporary ecological dimension to soil
1076 biology without a habitat? Soil Biology & Biochemistry 30, 1229-1232.

1077 Young, I.M., Crawford, J.W., Rappoldt, C., 2001. New methods and models for
1078 characterising structural heterogeneity of soil. Soil & Tillage Research, 61, 33-45

1079 Young, I.M., Crawford, J.W., 2004. Interactions and self-organization in the soil-
1080 microbe complex. Science 304, 1634-1637.

- 1081 Young, I.M., Ritz, K., 2005. The habitat of soil microbes. In: Bardgett, R.D., Usher,
1082 M.B., Hopkins, D.W., (Eds.), Biological diversity and function in soils.
1083 Cambridge University Press, Cambridge, pp. 31-43.

Advantages

- Improved transmission of secondary ions at high mass and spatial resolution
- Multi-collector: Simultaneous collection of up to five ion species¹
- Full periodic table (H-U)
- Distinction between isotopes of elements
- Increased sensitivity (ppm)
- Improved resolution through co-axial optics (i.e. 90° incident angle), low pA beam currents and short working distance:
Lateral resolution of 50 nm (Cs⁺ primary ion beam) and 150 nm (O⁻ primary ion beam)
Depth resolution of 1 nm
- Navigation:
CCD camera assists in navigation
- Mini Scanning Electron Microscope (Cs⁺ primary ion beam only):
Secondary Electron collection and imaging; revealing surface details
- Electron gun (Cs⁺ primary ion beam only):
Charge compensation

1085

1086 ¹ The Cameca NanoSIMS 50L is capable of collecting seven ion species

1087 simultaneously.

1088 **Figure legends:**

1089 Figure 1: Biochemical processes versus techniques at different physical scales.

1090 Figure 2: Schematics of NanoSIMS Ion Optics. R = Radius of the secondary ion
1091 trajectories (figure kindly provided by Frank J. Stadermann, Washington
1092 University, St Louis, Missouri,
1093 <http://presolar.wustl.edu/nanosims/schematic.html>).

1094 Figure 3: Typical NanoSIMS images of a cross section of ^{15}N -labelled
1095 *Pseudomonas fluorescens* mixed in coarse textured sand and embedded in
1096 Araldite resin. (A) $^{12}\text{C}^-$ (grey); (B) $^{28}\text{Si}^-$ (blue); (C) $^{12}\text{C}^{14}\text{N}^-$ (green) and (D)
1097 $^{15/14}\text{N}$ ratio (red). Four electron-multiplier secondary ion detectors were
1098 used to simultaneously collect $^{12}\text{C}^-$, $^{12}\text{C}^{14}\text{N}^-$, $^{12}\text{C}^{15}\text{N}^-$ and $^{28}\text{Si}^-$ data with the
1099 nominal size of images between 12 μm field of view. The mass resolving
1100 power was ~ 5000 and spatial resolution was ~ 100 nm probe diameter.
1101 Maps representing $^{15/14}\text{N}$ ratios were obtained by dividing the $^{12}\text{C}^{15}\text{N}^-$
1102 counts by $^{12}\text{C}^{14}\text{N}^-$ counts for each pixel, using the MIMS plug-in for the
1103 freeware package, Image J (image processing technique available at
1104 <http://rsb.info.nih.gov/ij/>).

1105 Figure 4: Cross section of ^{15}N -labelled *Pseudomonas fluorescens* mixed in coarse
1106 textured sand: (A) Superimposed NanoSIMS images (blue = $^{28}\text{Si}^-$; green =
1107 $^{12}\text{C}^{14}\text{N}^-$ and red = $^{15/14}\text{N}$ ratio) (field of view = 12 μm) and (B) Mosaic of
1108 $^{28}\text{Si}^-$ ion images (blue) and $^{12}\text{C}^{14}\text{N}^-$ (green), superimposed with $^{15/14}\text{N}$ ratio
1109 images (red) (field of view = 30 μm for each ion image and step between
1110 images of 25 μm giving a total field of view of 105 x 55 μm).

1111 Figure 5: Soil particles from a sandy soil amended with ^{13}C and ^{15}N -labelled *Pinus*
1112 *ponderosa* fine roots and needles (Bird and Torn, 2006). (A) NanoSIMS
1113 $^{12}\text{C}^-$ image of a $15\ \mu\text{m}$ field of view of an uncoated soil particle, dried and
1114 pressed into an aluminium stub. (B) NanoSIMS $^{13/12}\text{C}$ image of the same
1115 region, coated with gold and using the electron flood gun. Image is an
1116 integration of 50 individual 256×256 pixel planes (scans). (Courtesy Drs
1117 Jennifer Pett-Ridge and Peter K. Weber, Lawrence Livermore National
1118 Laboratory and Dr Jeffrey Bird, University of California Berkeley, USA).

1119 Figure 6: Soil particles from a sandy soil amended with ^{13}C and ^{15}N -labelled *Pinus*
1120 *ponderosa* fine roots and needles (Bird and Torn, 2006). (A) Montage of
1121 multiple transmission electron microscopy images (FEI Tecnai 12 120KV
1122 Transmission Electron Microscope) of a single soil particle, embedded in
1123 sulphur (Bradley et al., 1993) and microtomed to $\sim 200\ \text{nm}$. (B)
1124 NanoSIMS image of $^{12}\text{C}^{14}\text{N}^-$ soil particle ($16\ \mu\text{m}$ field of view) of
1125 putative fungal hyphae (area is depicted as red box in (A)) and detailed
1126 NanoSIMS image of (C) $^{12}\text{C}^{14}\text{N}^-$ and (D) P^- ($5\ \mu\text{m}$ field of view, mass
1127 resolving power was >7000 , integration of 20 individual 256×256 pixel
1128 planes; area is depicted as white box in (B)). Its relatively lower P content
1129 (Figure 6d) to the background suggests that this feature may be a ‘ghost
1130 hyphae’, i.e. the shell marking where live tissue once existed. (Courtesy
1131 Drs Jennifer Pett-Ridge and Peter K. Weber, Lawrence Livermore
1132 National Laboratory and Dr Jeffrey Bird, University of California
1133 Berkeley, USA).

1134 *This work was performed under the auspices of the U.S. Department of Energy by
1135 the University of California, Lawrence Livermore National Laboratory under Contract
1136 No. W-7405-Eng-48
1137
1138 UCRL-JRNL-225506