Organic LETTERS

Letter

pubs.acs.org/OrgLett

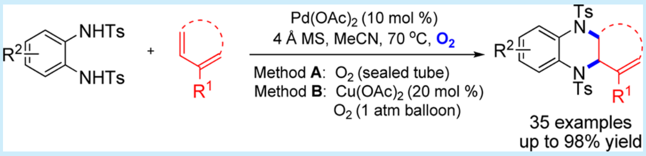
Pd(II)-Catalyzed Aerobic Intermolecular 1,2-Diamination of Conjugated Dienes: A Regio- and Chemoselective [4 + 2] Annulation for the Synthesis of Tetrahydroquinoxalines

Zhengxing Wu, Ke Wen, Jingang Zhang, and Wanbin Zhang*

School of Chemistry and Chemical Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, P. R. China

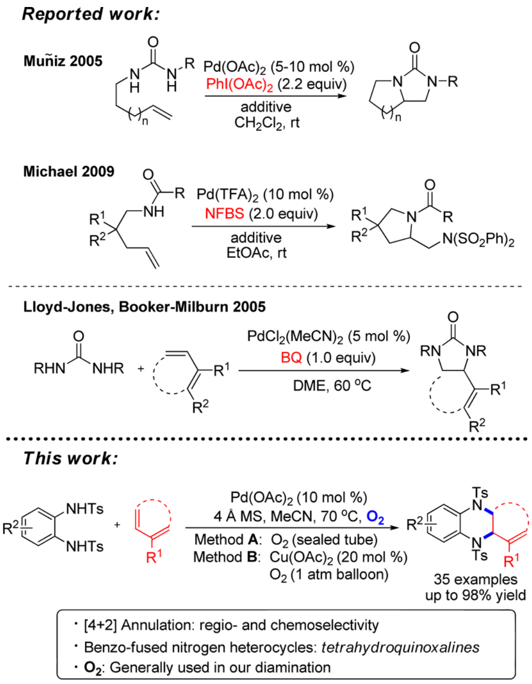
Ⓢ *Supporting Information*

ABSTRACT: A Pd(II)-catalyzed aerobic intermolecular 1,2-diamination of conjugated dienes was developed for the regio- and chemoselective preparation of a variety of functionalized tetrahydroquinoxalines, using simple sulfonyl protected *o*-phenylendiamines as a nitrogen source. This methodology provides a direct and efficient synthesis of tetrahydroquinoxalines. O_2 was used as the stoichiometric oxidant, and reaction conditions were applied to a series of *o*-phenylendiamines and conjugated dienes. 35 examples are described, and good yields and selectivities are obtained for the majority of the products.



Vicinal diamines are important compounds found in a wide range of biologically active compounds, synthetic intermediates, and organocatalysts.[1,2] The direct 1,2-diamination of alkenes offers an especially efficient method for the synthesis of vicinal diamines. In recent decades, several metal-mediated,[1,3] metal-catalyzed,[1,4−7] and metal-free[1,8] methods have been reported. Among these methods, Pd-catalyzed diamination is one of the most important processes.[5−7] Shi et al. carried out a number of pioneering investigations concerning Pd(0)-catalyzed 1,2-diaminations.[5] Several intra- and intermolecular Pd(II)-catalyzed oxidative 1,2-diaminations using isolated alkenes have also been reported (Scheme 1).[6] Muñiz et al. developed a series of intra- and intermolecular Pd(II)-catalyzed 1,2-diaminations for isolated alkenes mainly using hypervalent iodine as an oxidant.[6a−c,g−j] Michael et al. reported Pd(II)-catalyzed 1,2-diaminations of isolated alkenes with *N*-fluorobenzenesulfonimide (NFSI) as an oxidant and a nitrogen source.[6e,f,k] However, examples concerning Pd(II)-catalyzed oxidative 1,2-diaminations with conjugated alkenes are uncommon. Lloyd-Jones and Booker-Milburn reported a seminal Pd(II)-catalyzed intermolecular diamination of conjugated alkenes using ureas as nitrogen sources, obtaining five-membered N-heterocycles with high yields using benzoquinone as an oxidant.[7] However, it is still generally difficult to use oxygen as an oxidant. Despite these successful cases, for current Pd-catalyzed 1,2-diaminations, the direct preparation of other valuable diamine products (such as benzo-fused heterocycles) using simple nitrogen sources requires further research; use of O_2 as an oxidant in oxidative 1,2-diaminations with alkenes also remains challenging due to difficulties encountered in active and selective transformations.[9] During our research concerning the Pd-catalyzed synthesis of heterocycles,[10] we developed a Pd(II)-catalyzed aerobic intermolecular 1,2-diamination of conjugated dienes using sulfonyl protected *o*-phenylendiamines as nitrogen sources, for the preparation of a variety of important functionalized tetrahydroquinoxalines (Scheme 1).[2]

Scheme 1. Pd-Catalyzed Oxidative 1,2-Diaminations



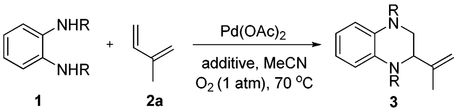
- [4+2] Annulation: regio- and chemoselectivity
- Benzo-fused nitrogen heterocycles: *tetrahydroquinoxalines*
- O_2: Generally used in our diamination

We commenced our study by screening the reactions between *N*-protected *o*-phenylendiamines **1** and isoprene **2a** in the presence of catalytic $Pd(OAc)_2$ (10 mol %) and $Cu(OAc)_2$ (20 mol %) under O_2 in MeCN at 70 °C (Table 1, entries 1−5). To our delight, for *N*-Ts protected *o*-phenylendiamine **1a**, although the reaction mixture was complex, the oxidative cyclization proceeded to give the desired product **3aa** in 23% yield, and the

Received: March 28, 2017

DOI: 10.1021/acs.orglett.7b00919
Org. Lett. XXXX, XXX, XXX−XXX

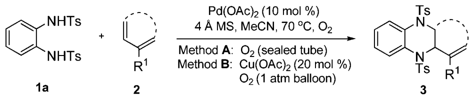
Table 1. Optimization of the Reaction Conditions[a]

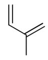
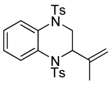
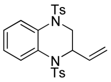
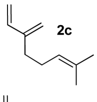
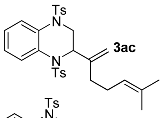
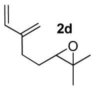
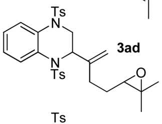
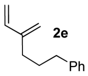
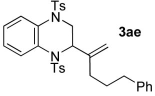
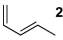
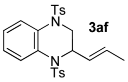
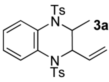
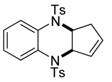
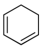
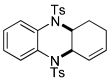
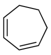
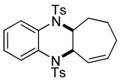


entry	R	Pd(OAc)$_2$ (mol %)	Cu(OAc)$_2$ (mol %)	diene 2a (equiv)	oxygen	yield (3)[b]
1	Ts (**1a**)	10	20	2	1 atm balloon	23 (**3aa**)
2	Ms (**1b**)	10	20	2	1 atm balloon	17 (**3ba**)
3	Ac (**1c**)	10	20	2	1 atm balloon	–
4	Boc(**1d**)	10	20	2	1 atm balloon	–
5	Cbz (**1e**)	10	20	2	1 atm balloon	–
6[c]	Ts	10	20	2	1 atm balloon	trace
7[d]	Ts	10	20	2	1 atm balloon	13
8	Ts	10	–	2	1 atm balloon	trace
9	Ts	–	20	2	1 atm balloon	–
10[e]	Ts	10	20	2	1 atm balloon	27
11[e]	Ts	10	20	10	1 atm balloon	35
12[e]	**Ts**	**10**	–	**10**	**sealed tube**	**82**
13[e]	Ts	10	20	10	sealed tube	37
14[e]	Ts	10	–	5	sealed tube	63
15[e]	Ts	5	–	10	sealed tube	59

[a]Unless otherwise noted, the reactions were carried out using 0.1 mmol of diamine **1**, Pd(OAc)$_2$, and isoprene **2a** in MeCN (2 mL) at 70 °C for 72 h under O$_2$. [b]Isolated yields. [c]The solvent is DME. [d]The solvent is DMSO. [e]4 Å molecular sieves (40 mg) were added.

Table 2. Scope of Conjugated Dienes for 1,2-Diamination[a]



entry	conjugated diene	product	method	yield (%)[b]
1	 **2a**	 **3aa**	**A** **B**	82 35
2	 **2b**	 **3ab**	**A** **B**	84 42
3[c]	 **2c**	 **3ac**	**A** **B**	96 trace
4[c]	 **2d**	 **3ad**	**A** **B**	95 trace
5[c]	 **2e**	 **3ae**	**A** **B**	85 trace
6	 **2f**	 **3af**  **3af'**	**A** **B**	42 (1.2:1) trace
7	 **2g**	 **3ag**	**A** **B**	35 34
8[d]	 **2h**	 **3ah**	**A** **B**	13 92
9[e]	 **2i**	 **3ai**	**A** **B**	28 55

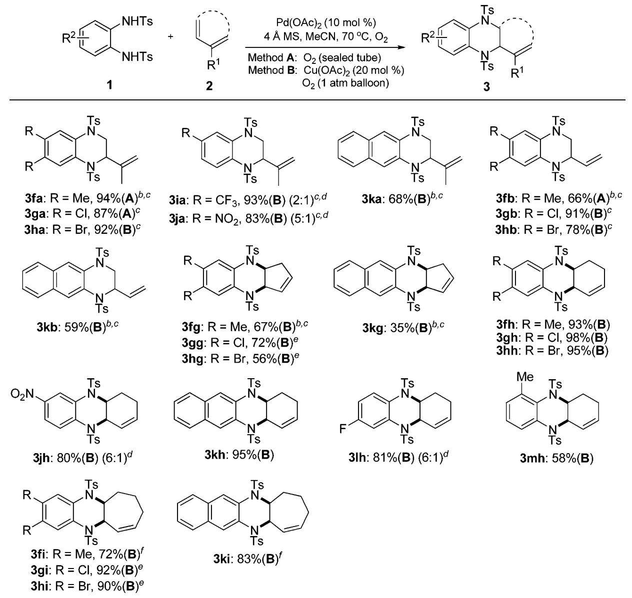
[a]Unless otherwise noted, the reactions were carried out using diamine **1a** (0.1 mmol), Pd(OAc)$_2$ (10 mol %), 4 Å molecular sieves (40 mg), and diene **2** (10 equiv) in MeCN (2 mL) at 70 °C for 72 h. Method A: In a sealed tube charged with O$_2$ (starting at 1 atm). Method B: Cu(OAc)$_2$ (20 mol %) under O$_2$ (1 atm balloon). [b]Isolated yields. [c]Diene **2** (2 equiv) for 48 h. [d]Diene **2** (2 equiv) for 12 h. [e]Diene **2** (5 equiv) and Pd(OAc)$_2$ (20 mol %).

1,4-diamination (regioselectivity) and 1,2-diamination at the more substituted double bond (chemoselectivity) were not detected (entry 1). The reaction of *N*-Ms protected *o*-phenylendiamine **1b** was also successful (entry 2); however, *o*-phenylendiamine bearing other Ac, Boc, or Cbz protecting groups (**1c**−**1e**) did not undergo reaction (entries 3−5). A range of solvents were then examined using *o*-phenylendiamine **1a**.[11] The yields in DME or DMSO were no better than that in MeCN, although product **3aa** was also obtained (entries 6, 7 vs entry 1). Control experiments were also carried out and compared to the initial conditions (entries 8, 9). A trace amount of product **3aa** was detected in the absence of Cu(OAc)$_2$ (entry 8 vs entry 1), and none of **3aa** was obtained in the absence of Pd(OAc)$_2$ (entry 9 vs entry 1). These suggested that Pd(OAc)$_2$ was essential for diamination and that Cu(OAc)$_2$ alone could not catalyze the reaction. Addition of 4 Å molecular sieves or increasing the amount of isoprene led to an increase in the yield of product **3aa** (entries 10, 11). Considering that the low boiling point of isoprene **2a** may reduce its concentration in the reaction system and thus hinder the reaction, the reaction was thus carried out in a sealed tube under O$_2$ (starting at 1 atm). Gratifyingly, the reaction proceeded well and a high yield (product **3aa** up to 82% yield) and selectivity were obtained (entry 12); the remaining material consisted mostly of unreacted substrate. We proposed that the increased amount of isoprene in the reaction system using a sealed tube may help promote the reaction and, more importantly, may act as a ligand to prevent the precipitation of palladium. Addition of Cu(OAc)$_2$ (20 mol %) led to a series of complex side products (entry 13 vs entry 12). When we decreased the amount of isoprene (entry 14 vs entry 12) and Pd(OAc)$_2$ (entry 15 vs entry 12) respectively, the corresponding yields were also reduced.

With the above optimized reaction conditions (Method A) in hand (Table 1, entry 12), a variety of conjugated dienes were surveyed to explore the scope of the reaction (Table 2). We discovered that, in addition to isoprene **2a** (Table 2, entry 1), 1,3-butadiene **2b** also underwent conversion with a good yield and selectivity (entry 2). The reaction conditions also could tolerate the alkenyl-substituted myrcene **2c**, giving the corresponding functionalized tetrahydroquinoxalines in high yields (entry 3). The diene **2d** bearing an epoxy group also underwent reaction in high yield (entry 4). For 2-substituted conjugated diene **2e** bearing aryl group, the reaction proceeded well, and a high yield and good selectivity could be obtained (entry 5). For terminal methyl-substituted 1,3-diene **2f**, the terminal diamination (**3af**)

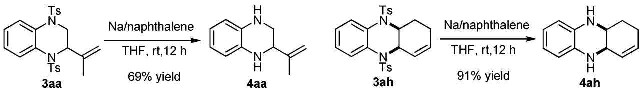
DOI: 10.1021/acs.orglett.7b00919
Org. Lett. XXXX, XXX, XXX−XXX

Scheme 2. Scope of Nitrogen Source for 1,2-Diamination[a]



[a]Unless otherwise noted, the reactions were carried out using diamine **1** (0.1 mmol), $Pd(OAc)_2$ (10 mol %), 4 Å molecular sieves (40 mg), and diene **2** (2 equiv) in MeCN (2 mL) at 70 °C for 12 h. Isolated yields. Method A: In a sealed tube charged with O_2 (starting at 1 atm). Method B: $Cu(OAc)_2$ (20 mol %) under O_2 (1 atm balloon). [b]For 72 h. [c]Diene **2** (10 equiv). [d]The ratios arising from the asymmetrical nature of the monosubstituted *o*-phenylendiamines were confirmed by analysis of the ^1H NMR spectrum of the crude reaction mixture. [e]For 24 h. [f]Diene **2** (5 equiv) for 72 h.

Scheme 3. Further Transformations of the Functionalized Tetrahydroquinoxalines



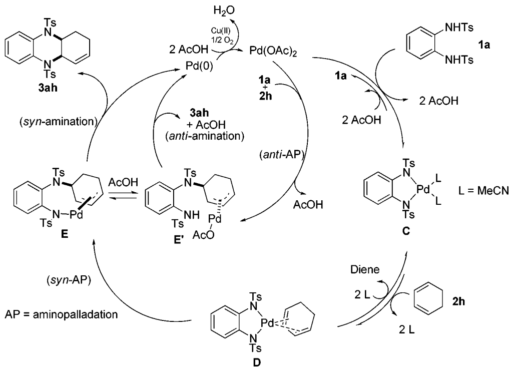
and internal diamination (**3af′**) of the diene occurred, giving the corresponding product in a total yield of 42% yield (entry 6, **3af**:**3af′** = 1.2:1). We also used a terminal phenyl-substituted 1,3-diene ((*E*)-buta-1,3-dienylbenzene) as a diene substrate; however, no reaction occurred. For the acyclic dienes mentioned above (entries 1−6), the reaction systems became complex and the diaminations were unsatisfactory in the presence of $Cu(OAc)_2$ (Method B). The cyclic conjugated diene, cyclopentadiene **2g**, could be converted to its corresponding product **3ag** using Method A or B, but both with a lower yield (entry 7).[12] However, for other cyclic conjugated dienes such as 1,3-cyclohexadiene **2h** (entry 8) and 1,3-cycloheptadiene **2i** (entry 9), $Cu(OAc)_2$ was essential to facilitate the conversion despite the appearance of some side products (Method B).

We next turned our attention to investigating the nitrogen source scope of the 1,2-diamination. Scheme 2 shows that a range of toluenesulfonyl protected *o*-phenylendiamines and conjugated dienes are able to participate in the oxidative cyclization using either Method A or B. The majority of the *o*-phenylendiamine substrates bearing both electron-donating and -withdrawing substituents were amenable to the reaction conditions using isoprene **2a**. The desired products (**3fa**−**3ka**) were obtained with high yields and good selectivities using isoprene **2a** (10 equiv); Method B provided better results for most of *o*-phenylendiamine substrates bearing electron-withdrawing substituents (**3ha**−**3ja**) and a naphthalene substrate (**3ka**) (the corresponding results using Method A were shown in the Supporting Information (SI)).[11,12] The annulation process also worked well when 1,3-butadiene **2b** (10 equiv) was subjected to reaction with various *o*-phenylendiamines possessing both electron-donating and -withdrawing groups (**3fb**−**3kb**), and the results were better for **3gb**−**3kb** using Method B (the corresponding results using Method A were also shown in the SI).[11] For cyclic conjugated dienes **2g**−**2i**, the desired products could be obtained diastereoselectively using Method B.[12] A series of products (**3fg**−**3kg**) could be generated using cyclopentadiene **2g** (2−10 equiv). Most diaminations using 1,3-cyclohexadiene **2h** (2 equiv) proceeded well with high yields (**3fh**−**3mh**), regardless of the substitution pattern.[12] For reactions involving 1,3-cycloheptadiene **2i** (2−5 equiv), a series of products (**3fi**−**3ki**) could be obtained in high yields.

The functionalized tetrahydroquinoxalines generated via intermolecular diamination could be transformed further. For example, the free tetrahydroquinoxalines **4aa** and **4ah** can be obtained from **3aa** and **3ah** by deprotection of the *N*-tosyl group with a Na/naphthalene solution respectively, with moderate to high yields (Scheme 3).

A proposed catalytic cycle is shown in Scheme 4. For simplicity, we chose **1a** and diene **2h** as representative examples. According to *in situ* ^1H NMR and HRMS studies,[11,5g,6c] substrate **1a** and $Pd(OAc)_2$ first form the five-membered Pd(II) species **C**, which may then be converted to the diene complex **D** via ligand exchange. The π-allyl Pd intermediate **E** is formed from complex **D** via an aminopalladation step (in previously reported work, the sulfonyl-protected amines predominantly favored *syn*-aminopalladation).[13] Another potential pathway involving $Pd(OAc)_2$, **1a**, and **2h** undergoing an *anti*-aminopalladation step to form π-allyl Pd intermediate **E′** cannot be excluded, due to the presence of an equilibrium for the formation of species **C** from $Pd(OAc)_2$ and **1a**. The π-allyl Pd intermediate **E** and **E′** may exist in equilibrium.[14] Finally, product **3ah** can be formed via two possible amination processes, and *anti*-amination from intermediate **E′** is favored with attack on the π-allyl Pd intermediate by soft nucleophiles such as sulfonamide.[15] The resulting Pd(0) is oxidized to Pd(II), which then participates in the next catalytic cycle.

Scheme 4. Proposed Catalytic Cycle



In conclusion, we have developed a general method for the Pd(II)-catalyzed aerobic intermolecular 1,2-diamination of conjugated dienes via [4 + 2] annulation. A class of important tetrahydroquinoxalines were synthesized regio- and chemoselectively. This methodology provides a direct and efficient synthesis in good yield using O_2 as the stoichiometric oxidant.

This methodology extends the significance of 1,2-diaminations, allowing for the preparation of valuable diamine products using simple nitrogen sources.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.7b00919.

Experimental procedures; spectral data (PDF)
Crystallographic data for **3ah** (CIF)
Crystallographic data for **3jh** (CIF)
Crystallographic data for **3mh** (CIF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: wanbin@sjtu.edu.cn.

ORCID

Wanbin Zhang: 0000-0002-4788-4195

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was partially supported by the National Natural Science Foundation of China (Nos. 21232004, 21672142), Program of Shanghai Subject Chief Scientists (No.14XD1402300), and the Basic Research Foundation of Shanghai Science and Technology Committee (No.15JC1402200). We also thank the Instrumental Analysis Center of Shanghai Jiao Tong University.

■ REFERENCES

(1) For selected reviews, see: (a) Bäckvall, J.-E. *Acc. Chem. Res.* **1983**, *16*, 335. (b) Bennani, Y. L.; Hanessian, S. *Chem. Rev.* **1997**, *97*, 3161. (c) Lucet, D.; Le Gall, T.; Mioskowski, C. *Angew. Chem., Int. Ed.* **1998**, *37*, 2580. (d) Muñiz, K. *Chem. Soc. Rev.* **2004**, *33*, 166. (e) Minatti, A.; Muñiz, K. *Chem. Soc. Rev.* **2007**, *36*, 1142. (f) Kizirian, J.-C. *Chem. Rev.* **2008**, *108*, 140. (g) Lin, G.-Q.; Xu, M.-H.; Zhong, Y.-W.; Sun, X.-W. *Acc. Chem. Res.* **2008**, *41*, 831. (h) de Figueiredo, R. M. *Angew. Chem., Int. Ed.* **2009**, *48*, 1190. (i) Cardona, F.; Goti, A. *Nat. Chem.* **2009**, *1*, 269. (j) Viso, A.; Fernández de la Pradilla, R.; Tortosa, M.; García, A.; Flores, A. *Chem. Rev.* **2011**, *111*, PR1. (k) Zhu, Y.; Cornwall, R. G.; Du, H.; Zhao, B.; Shi, Y. *Acc. Chem. Res.* **2014**, *47*, 3665.

(2) For selected examples of tetrahydroquinoxalines: (a) Schuyler, P.; Popp, F. D.; Noble, A. C.; Alwani, D. W.; Masters, B. R. *J. Med. Chem.* **1966**, *9*, 704. (b) Barrows, T. H.; Farina, P. R.; Chrzanowski, R. L.; Benkovic, P. A.; Benkovic, S. J. *J. Am. Chem. Soc.* **1976**, *98*, 3678. (c) Bianchini, C.; Barbaro, P.; Scapacci, G.; Farnetti, E.; Graziani, M. *Organometallics* **1998**, *17*, 3308. (d) Yang, S. C.; Shue, Y. J.; Liu, P. C. *Organometallics* **2002**, *21*, 2013. (e) Sikorski, J. A. *J. Med. Chem.* **2006**, *49*, 1. (f) Borrok, M. J.; Kiessling, L. L. *J. Am. Chem. Soc.* **2007**, *129*, 12780. (g) Eary, C. T.; Jones, Z. S.; Groneberg, R. D.; Burgess, L. E.; Mareska, D. A.; Drew, M. D.; Blake, J. F.; Laird, E. R.; Balachari, D.; O'Sullivan, M.; Allen, A.; Marsh, V. *Bioorg. Med. Chem. Lett.* **2007**, *17*, 2608.

(3) The first Pd(II)-mediated 1,2-diamination of isolated alkene, see: (a) Bäckvall, J. E. *Tetrahedron Lett.* **1978**, *19*, 163. Other selected metal-mediated 1,2-diaminations, for Os: (b) Chong, A. O.; Oshima, K.; Sharpless, K. B. *J. Am. Chem. Soc.* **1977**, *99*, 3420. (c) Muñiz, K.; Nieger, M.; Mansikkamäki, H. *Angew. Chem., Int. Ed.* **2003**, *42*, 5958. Co: (d) Becker, P. N.; White, M. A.; Bergman, R. G. *J. Am. Chem. Soc.* **1980**, *102*, 5676. Se: (e) Bruncko, M.; Khuong, T.-A. V.; Sharpless, K. B. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 454. Cu: (f) Zabawa, T. P.; Kasi, D.; Chemler, S. R. *J. Am. Chem. Soc.* **2005**, *127*, 11250. (g) Sequeira, F. C.; Turnpenny, B. W.; Chemler, S. R. *Angew. Chem., Int. Ed.* **2010**, *49*, 6365.

(4) For selected examples of metal-catalyzed 1,2-diamination, for Rh: (a) Li, G.; Wei, H.-X.; Kim, S. H.; Carducci, M. D. *Angew. Chem., Int. Ed.* **2001**, *40*, 4277. (b) Olson, D. E.; Su, J. Y.; Roberts, D. A.; Du Bois, J. *J. Am. Chem. Soc.* **2014**, *136*, 13506. Ni: (c) Muñiz, K.; Streuff, J.; Hövelmann, C. H.; Núñez, A. *Angew. Chem., Int. Ed.* **2007**, *46*, 7125. Au: (d) Iglesias, A.; Muñiz, K. *Chem. - Eur. J.* **2009**, *15*, 10563. Cu: (e) Sequeira, F. C.; Turnpenny, B. W.; Chemler, S. R. *Angew. Chem., Int. Ed.* **2010**, *49*, 6365. (f) Zhao, B.; Peng, X.; Zhu, Y.; Ramirez, T. A.; Cornwall, R. G.; Shi, Y. *J. Am. Chem. Soc.* **2011**, *133*, 20890.

(5) For selected examples of Pd(0)-catalyzed 1,2-diaminations: (a) Du, H.; Zhao, B.; Shi, Y. *J. Am. Chem. Soc.* **2007**, *129*, 762. (b) Du, H.; Yuan, W.; Zhao, B.; Shi, Y. *J. Am. Chem. Soc.* **2007**, *129*, 7496. (c) Du, H.; Yuan, W.; Zhao, B.; Shi, Y. *J. Am. Chem. Soc.* **2007**, *129*, 11688. (d) Wang, B.; Du, H.; Shi, Y. *Angew. Chem., Int. Ed.* **2008**, *47*, 8224. (e) Du, H.; Zhao, B.; Shi, Y. *J. Am. Chem. Soc.* **2008**, *130*, 8590. (f) Fu, R.; Zhao, B.; Shi, Y. *J. Org. Chem.* **2009**, *74*, 7577. (g) Zhao, B.; Du, H.; Cui, S.; Shi, Y. *J. Am. Chem. Soc.* **2010**, *132*, 3523. (h) Cornwall, R. G.; Zhao, B.; Shi, Y. *Org. Lett.* **2013**, *15*, 796.

(6) For examples of Pd(II)-catalyzed 1,2-diaminations of isolated alkenes: (a) Streuff, J.; Hövelmann, C. H.; Nieger, M.; Muñiz, K. *J. Am. Chem. Soc.* **2005**, *127*, 14586. (b) Muñiz, K. *J. Am. Chem. Soc.* **2007**, *129*, 14542. (c) Muñiz, K.; Hövelmann, C. H.; Streuff, J. *J. Am. Chem. Soc.* **2008**, *130*, 763. (d) Muñiz, K.; Hövelmann, C. H.; Campos-Gomez, E.; Barluenga, J.; González, J. M.; Streuff, J.; Nieger, M. *Chem. - Asian J.* **2008**, *3*, 776. (e) Sibbald, P. A.; Michael, F. E. *Org. Lett.* **2009**, *11*, 1147. (f) Sibbald, P. A.; Rosewall, C. F.; Swartz, R. D.; Michael, F. E. *J. Am. Chem. Soc.* **2009**, *131*, 15945. (g) Iglesias, Á.; Pérez, E. G.; Muñiz, K. *Angew. Chem., Int. Ed.* **2010**, *49*, 8109. (h) Muñiz, K.; Kirsch, J.; Chávez, P. *Adv. Synth. Catal.* **2011**, *353*, 689. (i) Martínez, C.; Muñiz, K. *Angew. Chem., Int. Ed.* **2012**, *51*, 7031. (j) Chávez, P.; Kirsch, J.; Streuff, J.; Muñiz, K. *J. Org. Chem.* **2012**, *77*, 1922. (k) Ingalls, E. L.; Sibbald, P. A.; Kaminsky, W.; Michael, F. E. *J. Am. Chem. Soc.* **2013**, *135*, 8854.

(7) For Pd(II)-catalyzed 1,2-diamination of conjugated alkenes, see: Bar, G. L. J.; Lloyd-Jones, G. C.; Booker-Milburn, K. I. *J. Am. Chem. Soc.* **2005**, *127*, 7308.

(8) For selected examples: (a) Li, G.; Kim, S. H.; Wei, H.-X. *Tetrahedron Lett.* **2000**, *41*, 8699. (b) Booker-Milburn, K. I.; Guly, D. J.; Cox, B.; Procopiou, P. A. *Org. Lett.* **2003**, *5*, 3313. (c) Röben, C.; Souto, J. A.; González, Y.; Lishchynskyi, A.; Muñiz, K. *Angew. Chem., Int. Ed.* **2011**, *50*, 9478. (d) Chávez, P.; Kirsch, J.; Hövelmann, C. H.; Streuff, J.; Martínez-Belmonte, M.; Escudero-Adán, E. C.; Martin, E.; Muñiz, K. *Chem. Sci.* **2012**, *3*, 2375. (e) Han, B.; Yang, X. L.; Fang, R.; Yu, W.; Wang, C.; Duan, X. Y.; Liu, S. *Angew. Chem., Int. Ed.* **2012**, *51*, 8816. (f) Röben, C.; Souto, J. A.; Escudero-Adán, E. C.; Muñiz, K. *Org. Lett.* **2013**, *15*, 1008.

(9) For selected reviews: (a) Stahl, S. S. *Angew. Chem., Int. Ed.* **2004**, *43*, 3400. (b) Stahl, S. S. *Science* **2005**, *309*, 1824. (c) Punniyamurthy, T.; Velusamy, S.; Iqbal, J. *Chem. Rev.* **2005**, *105*, 2329. (d) Sigman, M. S.; Jensen, D. R. *Acc. Chem. Res.* **2006**, *39*, 221. (e) Bäckvall, J.-E. *Modern Oxidation Methods*, 2nd ed.; Wiley-VCH, Weinheim, 2011.

(10) (a) Zhang, Y.-J.; Wang, F.; Zhang, W. *J. Org. Chem.* **2007**, *72*, 9208. (b) Yang, G.; Zhang, W. *Org. Lett.* **2012**, *14*, 268. (c) Yang, G.; Shen, C.; Zhang, W. *Angew. Chem., Int. Ed.* **2012**, *51*, 9141. (d) Yang, G.; Zhang, W. *Angew. Chem., Int. Ed.* **2013**, *52*, 7540. (e) Kou, X.; Li, Y.; Wu, L.; Zhang, X.; Yang, G.; Zhang, W. *Org. Lett.* **2015**, *17*, 5566.

(11) See the SI.

(12) For the structure determination of **3ia**, **3ja**, **3jh**, **3lh**, **3mh** and products involving **2g**−**2i**, see the chapter concerning X-ray Crystal Structure Analysis in the SI.

(13) For a review, see: (a) McDonald, R. I.; Liu, G.; Stahl, S. S. *Chem. Rev.* **2011**, *111*, 2981. For selected examples: (b) Liu, G.; Stahl, S. S. *J. Am. Chem. Soc.* **2006**, *128*, 7179. (c) Liu, G.; Stahl, S. S. *J. Am. Chem. Soc.* **2007**, *129*, 6328. (d) White, P. B.; Stahl, S. S. *J. Am. Chem. Soc.* **2011**, *133*, 18594.

(14) For selected reviews, see: (a) Hayashi, T. *Acc. Chem. Res.* **2000**, *33*, 354. (b) Trost, B. M.; Machacek, M. R.; Aponick, A. *Acc. Chem. Res.* **2006**, *39*, 747. For related examples: (c) Mino, T.; Shiotsuki, M.; Yamamoto, N.; Suenaga, T.; Sakamoto, M.; Fujita, T.; Yamashita, M. *J. Org. Chem.* **2001**, *66*, 1795. (d) Kawatsura, M.; Terasaki, S.; Minakawa, M.; Hirakawa, T.; Ikeda, K.; Itoh, T. *Org. Lett.* **2014**, *16*, 2442.

(15) Trost, B. M.; Van Vranken, D. L. *Chem. Rev.* **1996**, *96*, 395.